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A key review on present status and future directions of solar energy studies and applications in Saudi Arabia

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ABSTRACT

Renewable energy is accepted as a key source for the future, not only for Saudi Arabia, but also for the world. Saudi Arabia has abundant potential for exploiting solar energy, which is renewable, clean, and freely available. The average annual solar radiation falling on the Arabian Peninsula is about 2200 kWh/m^2. Applications of solar energy in Saudi Arabia have been growing since 1960. Solar hydrogen production plant situated at the Solar Village, Riyadh, Saudi Arabia, could have been considered as the world's first 350 kW solar-powered hydrogen-generation plant at the time of its inception. The development of solar energy, however, has been relatively low due to several obstacles although utilization of solar energy in its various aspects is very attractive for the country. The main objectives of this study are to address current applications and future aspects of solar energy along with studies conducted in this field and to assess them in the light of available sustainable energy technologies towards establishing energy policies. The solar energy-related topics reviewed include various types of solar radiation correlations, exergetic solar radiation, solar collectors, solar photovoltaic (PV) systems, solar stills, solar-powered irrigation, solar energy-related greenhouses, solar hydrogen, solar water desalination and solar energy education. Some barriers, scenarios and constraints are also covered. The utilization of solar energy could cover a significant part of the energy demand in the country. If a major breakthrough is achieved in the field of solar-energy conversion, Saudi Arabia can be a leading producer and exporter of solar energy in the form of electricity. The geographical location of the country, its widespread unused desert land, and year-round clear skies, all make it an excellent candidate for this.

Contents

Abbreviations: ANN, artificial neural network; ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; COE, cost of generating energy; COP, coefficient of performance; CoRE-RE, Center of Research Excellence in Renewable Energy; ED, electrodialysis; ERI, Energy Research Institute; GCC, Gulf Cooperation Council; GH, greenhouse; GSR, global solar radiation; HYSOLAR, A Long-term German-Saudi Arabian Cooperative Programme for research, development and demonstration of solar hydrogen production as well as utilization of hydrogen as an energy carrier; KACARE, King Abdullah City for Atomic and Renewable Energy; KACST, King Abdulaziz City for Science and Technology; KAUST, King Abdullah University of Science and Technology; KFUPM, King Fahd University of Petroleum and Minerals; KSU, King Saud University; MD, membrane distillation; MSF, multistage flash desalination; NREL, National Research Energy Laboratory; PCM, phase change material; PTC, parabolic-trough collectors; RBF, radial basis function; R&D, research and development; RD&D, research, development and demonstration; RO, reverse osmosis; SERI, Solar Energy Research Institute; SET, sustainable energy technology; SOLERAS, Solar Energy Research American Saudi: Saudi Arabian-United States Program for cooperation in the field of solar energy program; VC, vapor compression.

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Nomenclature

a,b	coefficient of regression models
C_w	amount of cloud cover (octas)
H	monthly average of daily global radiation on horizontal surface (W/m^2 day)
H_b	monthly average of daily beam radiation on horizontal surface (W/m^2 day)
H_d	monthly average of daily diffuse radiation on horizontal surface (W/m^2 day)
H_D	diffuse irradiation on horizontal surface (Wh/m^2 day)
H_G	global solar irradiation (Wh/m^2 day)
H_0	monthly average of daily extraterrestrial radiation on horizontal surface (W/m^2 day)
K	geographical factor
K_t	monthly average of daily clearness index
L_l	latitude of location (°)
$MABE$	mean absolute bias error
MBE	mean bias error
MPE	mean percentage error
P_{at}	atmospheric pressure (kPa)
PWV	perceptible water vapor
R	coefficients of correlation
R^2	coefficient of determination
R_h	relative humidity (%)
$RMSE$	root mean square error
S	monthly average of daily bright sunshine hours (h)
S_c	solar energy absorbed by the greenhouse cover (W/m^2)
S_G	solar energy incident on the greenhouse (W/m^2)
S_L	solar energy lost to outside the greenhouse (W/m^2)
S_0	monthly mean daily maximum possible sunshine-duration
S_p	solar energy absorbed by the plants (W/m^2)
S_s	solar energy absorbed by the soil (W/m^2)
S_w	solar energy absorbed by the humid inside air (W/m^2)
SS	sunshine duration (h)
t	time (day)
T	temperature (°C)
T_a	air temperature (°C)
T_{max}	maximum ambient (air) temperature (°C)
T_{min}	minimum ambient (air) temperature (°C)
Z	maximum possible daylight hours (h)
θ	doubling time (h)
ϕ	latitude of the monitoring station (°)
ψ	monthly averaged relative humidity factor

1. Introduction

The combined effects of the depletion of fossil fuels and the gradually emerging consciousness about environmental degradation have given the first priority to the use of renewable alternative energy resources in the 21st century [1]. Of all renewables, solar thermal energy is considered to be practically unlimited in the long-term, and is a very abundant resource in the developing world [2]. It is potential source of renewable energy options that is being pursued by a number of countries with monthly average daily solar radiation in the range of 3–6 kWh/m^2, in an effort to reduce their dependence on fossil-based nonrenewable fuels [3].

Saudi Arabia is located in the heart of one of the world's most productive solar regions, which receive the most potent kind of sunlight [4]. The average annual solar radiation falling on the Arabian Peninsula is about 2200 kWh/m^2 [5].

Utilization of solar energy in its various aspects, therefore, is very attractive in this part of the world. Research, development, and demonstration (RD&D) activities in Saudi Arabia have confirmed that solar energy has a multitude of practical uses [6]. Renewable energy stands at something of a crossroads in Saudi Arabia. On the one hand, there have been serious energy analysts in the country who have worked for a greater role of solar energy in national energy policy. Renewable energy is widely praised for the environmental and public benefits it offers. On the other hand, there is a prevailing perception that renewable energy is largely irrelevant in the near- to mid-term planning horizons of industrial and energy investment in the Kingdom. This perception is manifested by the relatively small expenditures on renewable energy demonstration and commercialization projects, in the general lack of consideration of renewable energy in national energy policy development, and in the limited investment capital devoted to renewable energy projects. Energy forecasts in the country project negligible penetrations of renewable energy well into this century [7].

Future energy systems need to be based on renewable energy technologies in order to minimize environmental impacts and account for the finite supply of fossil fuels. The energy vector that holds the most promise for future energy systems is hydrogen. There remain, however, several challenges that must be addressed before a renewable hydrogen energy system can be implemented. The use of a carbon-based feedstock for hydrogen production in the near term cannot be avoided, but long-term solutions must be designed now to ensure energy needs are met in the future. The environmental, economical, and political reasons for the adoption of a renewable energy system emphasize the importance of its adoption [8].

In this regard, the importance of sustainable energy technologies (SETs) is emphasized as solutions to the development and climate needs. These technologies are expected to adapt to local conditions, promote efficient use of resources and facilitate improvement in living standards with minimal adverse impact on environment. Moreover SETs are required to be robust, reliable, user friendly and suitable to the needs of inaccessible localities. With all these qualities, SETs need to be available at a price affordable to people. Potentially, SETs are seen as instrumental to energy universalization in the developing countries by providing access to modern energy services to the people deprived of conventional energy services. Additionally, SETs, for their clean energy sources and high energy saving potential are expected to act as a preventive and curative measure to climate change [9].

The main objectives of this study are to present the current status and future aspects of solar energy in Saudi Arabia by comprehensively reviewing various solar-energy related studies conducted up to date and to highlight some corresponding available sustainable energy technologies towards establishing energy policies. In this regard, the structure of the paper consisting of eight sections is organized as follows: The first section gives some introductory information; Section 2 summarizes the historical development of solar energy in Saudi Arabia, while energy strategy and policy along lessons learnt from solar energy projects in Saudi Arabia are presented in Sections 3 and 4; present status of solar energy studies is reviewed in Section 5 in terms of various aspects, such as solar radiation resources, estimating solar radiation and exergetic solar radiation using various approaches, other solar energy-related research studies and studies on solar energy utilization, development and applications.

Section 6 includes future directions of solar energy studies in the lift of some recent advances in the field; some barriers, scenarios and constraints are covered and discussed in Section 7, while the last section concludes.

2. Brief historical development of solar energy

Applications of solar energy in Saudi Arabia have been growing since the early 1960s, when the first photovoltaic (PV) beacon was established by the French at the small airport of Madinah Al-Munnawara [10]. Research activities were commenced with small-scale university projects during 1969, while the systematized major research and development (R&D) works for the development of solar energy technologies were initiated by the King Abdulaziz City for Science and Technology (KACST) in 1977. For the last two decades the Energy Research Institute (ERI) at KACST has conducted major RD&D work in this field [6].

The ERI has conducted a number of international joint programs in the field of solar energy. In October, 1977, Saudi Arabia and the United States signed a project agreement for cooperation in the field of solar energy under the Solar Energy Research American Saudi: Saudi Arabian-United States Program for cooperation in the Field of Solar Energy Program (SOLERAS). The Solar Energy Research Institute (SERI) has been designated as the Operating Agent for the SOLERAS program [11]. SOLARES addressed solar energy in terms of both technological and economic issues. One of the several projects being conducted under SOLERAS supplied two traditional Saudi Arabian villages, not connected to the central electric grid, with solar energy. These first villages of Al-Jubaila and Al-Uyaina were realized in the early 1980 as an innovation for the region. Saudi Arabia was the first country in the Gulf Cooperation Council (GCC) countries as well as in the entire Middle East to research how to make villages independent from the central system of power production. SOLERAS was established in 1975 and concluded in 1997 [4,12]. After the pilot schemes to develop solar energy in the 1980s, Saudi Arabia has taken a much more active approach to solar power development [4].

A Long-term German-Saudi Arabian Cooperative Programme for Research, Development and Demonstration of Solar Hydrogen Production as well as Utilization of Hydrogen as an Energy Carrier (HYSOLAR) was started in 1986 with the Federal Republic of Germany. The first phase of HYSOLAR ended in 1991, focused mainly on investigation, test and improvement of hydrogen production technologies, while in the second phase contents, more emphasis was laid on hydrogen utilization technologies [13]. The SOLARES program was a unique bilateral, international, cooperative research effort. The US Department of Energy and the Saudi Arab National Center for Science and Technology (SANCST) had each committed US$50 million to this program, while the Solar Energy Research Institute (SERI) in Golden, Colorado, was responsible for it.

These joint programs were directed towards projects that were of mutual interest to the committed countries involved and concentrated on large demonstration projects such as electricity generation, water desalination, agricultural applications, and cooling systems [5].

In view of the importance of the need for exact measurements of solar radiation, the Saudi Atlas Project was initiated in 1994, as a joint R&D project between the ERI and the National Research Energy Laboratory (NREL) in the U.S. Twelve locations in the following cities throughout the country were carefully selected: Riyadh, Gassim, Al-Ahsa, Al-Jouf, Tabuk, Madinah, Jeddah, Qaisumah, Wadi Al Dawasir, Sharurah, Abha, and Gizan. All of these stations are connected to a central unit for data collection and all the instruments are calibrated on a regular basis (at 6-month periods) in order to derive reliable and accurate data [5]. In this regard, NREL and KACST realized the value of accurate surface solar radiation flux measurements for validation of satellite derived surface and atmospheric solar radiation flux measurements, and is making this data available to support validation of satellite data products related to the NASA Mission to Planet Earth component of the Earth Science Enterprise Earth Observing System (EOS) project to evaluate long term climate trends based on measurements from EOS Terra Platforms. Until April 18, 2000, the data available for the Saudi Network stations was quality assessed and flagged based on the use of a single composite calibration factor for the pyranometer deployed at each station. As of April 18, 2000, the global horizontal data posted for all of 1998 to date has been corrected for the cosine response of the individual pyranometer deployed at each station [14].

In March 2008, Saudi Arabia's oil minister, Ali Al-Naimi, stated that Saudi Arabia's strategic plan is to sharpen its solar energy expertise, essentially that Saudi Arabia enjoys in the oil industry. Al-Naimi advised the French Newsletter Petrostrategies: "One of the research efforts that we are going to undertake is to see how we make Saudi Arabia a center for solar energy research, and hopefully over the next 30–50 years, we will be a major megawatt exporter" [4,15].

The Kingdom of Saudi Arabia has begun building the first solar-powered water desalination plant in 2010, the first step in a

three-part program to give significant boost to the development of solar energy sector in the country [16,17]. Under the terms of an agreement signed last June, Saudi Aramco are to develop a pilot solar power plant that will have a capacity of 10 MW and is due to come on stream in 2011. Another 20 MW solar power plant is due to be built at King Abdullah University of Science and Technology, along with a center devoted to PV technology (Arab states may become solar energy exporters).

3. Energy strategy and policy

The Science and Technology National Policy draws up the broad lines of the future general directions of the science, technology and innovation in the Kingdom system of Saudi Arabia, to lay down an integrated guidance framework, which will serve as a reference basis to ensure the continuation of the system development efforts and the enhancement of its performance in the way that achieves the objectives sought by the Kingdom, in the long-term. The framework of this policy consists of principles and bases which define its directions, and general goals and objectives. The policy is also compliant with the general directions and objectives of the national development plans and the different sectorial policies and plans in the Kingdom [18].

The KACST, which has currently over 2500 employees and is an independent scientific organization administratively reporting to the Prime Minister, has played a significant role in developing solar energy technologies throughout the country since 1977. It is both the Saudi Arabian national science agency and its national laboratories. The science agency function involves science and technology policy making, data collection, funding of external research, and services such as the patent office [18,19].

The strategic objectives of the KACST are listed below [19].

(a) A sustained planning mechanism for all scientific disciplines.
(b) Scientifically knowledgeable and capable government agencies.
(c) A developed R&D infrastructure with fully functioning centers of excellence in all scientific disciplines.
(d) Strong interaction between the private sector and research centers.
(e) Regional leaders in patent ownership and issuance. Advanced incubator systems and output.
(f) World leaders in strategic technologies including water and oil and gas.
(g) Enhanced interaction networks between all scientific agencies.

In establishing energy polices, energy strategy is of big importance. In this regard, Abaoud and Veziroglu [20] proposed the following outline for Saudi Arabia.

(a) Establishing an energy organization, which may consist of various agencies, i.e., Ministry of Planning, Ministry of Petroleum and Mineral Resources, Ministry of Industry and Electricity, Petroleum and Petrochemical Companies, Desalination Organization and some Research Institutions.
(b) Conducting an assessment of all possible energy resources.
(c) Undertaking research and development programs for the promising resources.
(d) Improving the relationship between research institutions and industries.
(e) Choosing the right strategic partners.
(f) Building energy data banks, including monitoring changes and trends in energy resources and technologies.
(g) Designing models for various energy system options.

In this context, Reiche [12] investigated energy policies of GCC countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates) in more detail. These countries are major oil and natural gas producing countries and hold approximately 40% of the world's proven oil and 23.6% of the world's proven gas reserves. Furthermore, the general perception of the world is that GCC is one of the main actors impeding international climate change negotiations. Per capita, they are also one of the top contributors to pollution in the world. In this regard, a switch towards more efficient use of fossil fuels and an increased share of renewable energies would have several benefits for the GCC countries: if the domestic use of fossil fuels were reduced, more oil and natural gas could be exported.

In the recent years, the awareness on renewable energy options has risen because the country's oil and gas reserves are deep and are not infinite, while Saudi Arabia must use its current wealth to prepare for a future with dwindling fossil fuels. In this regard, researchers have welcomed a plan by Saudi Arabia to build a new renewable-energy "city" as a sign of the oil-rich nation's commitment to developing alternative fuel sources. The King Abdullah City for Atomic and Renewable Energy (KACARE) will serve as a center for renewables research and for co-coordinating national and international energy policy. It is expected that establishment of the city will contribute to achieving sustainable development in Saudi Arabia through exploiting the science, research and industry of atomic and renewable energy for peaceful purposes. The announcement to create the new city comes just 6 months after the official opening of the King Abdullah University of Science and Technology (KAUST), which is a multi-billion dollar research center with energy and environment among its core research activities and has a vision of providing a world-class university that can develop, among other things, more sustainable technologies. In addition, some universities, such as King Fahd University of Petroleum and Minerals (KFUPM), Dhahran and King Saud University (KSU), Riyadh established a Center of Research Excellence in Renewable Energy (CoRE-RE) and Sustainable Energy Technologies (SET) Center, respectively. It is expected that all these relatively new establishments will significantly make a contribution to the utilization and development of renewable sources of energy as well as rebuilding energy policies in the Kingdom.

It is also reported that setting up the KACST points out moving to a new phase that benefits from the varied and accumulated expertise of the Kingdom through the national research centers whether in the KACARE that includes the Atomic Energy Research Institute, the National Center of Protection from Radiation, the Energy Research Institute and the Solar Village in AlOnainia that was assigned with this task before or through the universities spread out in the Kingdom. All KACST capabilities would be put at the disposal of the new city and they would be positively functioned to boost the KACST and work together to secure a quick launch to this new city the achieve the strategic goals that the government has assigned to it [21].

4. Lessons learnt from solar energy projects in Saudi Arabia

Before reviewing the current status of solar energy studies in Saudi Arabia, it is very essential to know the lessons learnt from implementing various projects in the country. Table 1 lists major solar energy-related studies and projects undertaken by the ERI in Saudi Arabia over a period between 1981 and 2000 [5,22]. These include a wide range of projects such as PV system, solar cooling/refrigeration, solar hydrogen, solar thermal dishes, solar dryers and desalination, solar radiation and wind energy measurements. In this regard, the lessons learnt from solar energy during the

Table 1
List of solar energy projects conducted by the ERI, KACST.

Period or year conducted	Location	Description of projects		Application purposes
		Type	Capacity	
1981–1987	Solar Village	PV system	350 kW (2155 MWh)	AC/DC electricity for remote areas
1981–1987	Saudi universities	Solar cooling	–	Developing of solar cooling laboratory
1986–1991	KAU, Jeddah	Solar hydrogen	2 kW (50 kWh)	Testing of different electrode materials for solar hydrogen plant
1986–1994	Solar Village	Solar-thermal dishes	2 pieces, 50 kW	Advanced solar stirling engine
1987–1990	Solar Village	PV test system	3 kW	Demonstration of climatic effects
1987–1993	Solar Village	PV hydrogen production	350 kW (1.6 MWh)	Demonstration plant for solar plant hydrogen production
1988–1993	Dammam	Energy management in buildings	–	Energy conservation
1988–1993	Al-Hassa, Qatif	Solar dryers	–	Food dryers (dates, vegetables, etc.)
1989–1993	Solar Village	Solar hydrogen generator	1 kW (20–30 kWh)	Hydrogen production, testing and measurement (laboratory scale)
Since 1990	Solar Village	Long-term performance of PV	3 kW	Performance evaluation
1993–1995	Solar Village	Internal combustion engine	–	Hydrogen utilization
1993–1997	Solar Village	Solar collectors development	–	Domestic, industrial, agricultural
1993–2000	Solar Village	Fuel cell development	100–1000 W	Hydrogen utilization
1994–1999	Sadous Village	PV water desalination	0.6 m^3	PV/RO interface per hour
1994–2000	12 stations	Solar radiation measurement	–	Saudi solar atlas
1994–2000	5 stations	Wind energy measurement	–	Saudi solar atlas
1996	Southern regions of Saudi Arabia	PV system	4 kW	AC/DC electricity for remote areas
1996	Muzahmia	PV in agriculture	4 kWp	AC/DC grid connected
1996–1997	Solar Village	Solar-thermal desalination	–	Solar distillation of brackish water
1996–1998	Solar Village	PV system	6 kW	PV grid connection
1999–2000	Solar Village	Solar refrigeration	–	Desert application

Adapted from [5,22].

implementation of the projects given in Table 1 have been reported by Alawaji [5] as follows:

(a) In the developing countries, it is not worth spending funds on basic research for developing renewable energy sources. Instead, such efforts should be directed to finding applications of those systems that have already been developed in industrialized nations.
(b) Investigators dealing with renewable energy have responsibilities beyond the scientific and technical aspects of research and beyond the efforts made for publication of their findings. These cover dissemination and utilization of scientific knowledge gained in laboratories, and interaction with potential users, policy makers, planners, and manufacturers.
(c) Seawater desalination by solar energy is still not cost-effective when compared to convention energy sources (gas and oil), as implemented in Saudi Arabia.
(d) Assessment projects on renewable energy resources have helped Saudi staff gain valuable experience, especially in various fields such as instrumentation, calibration, data collection, and monitoring and analysis.
(e) The solar-thermal dish project revealed that development of thermal dishes with a smaller diameter would be more practical for remote applications because the operational and maintenance problems of large-scale dishes are complex and they are not cost-effective.
(f) Hydrogen production by PV systems can be used to store solar energy in a convenient form that can subsequently be used at a time of need; for example, power generation and domestic applications.
(g) For maintaining an acceptable level of system output, the PV array should be regularly cleaned under dusty weather conditions.
(h) PV systems have proven cost-effective in Saudi Arabia in supplying the peak demand of the electricity grid, as well as in supplying energy for small loads at remote sites.
(i) Close contacts and effective interaction need to be maintained between centers of R&D and local industry in order to bring the new developed product to practice.
(j) There is a need to promote proper education and technical training on renewable energy applications within academia, as well as a need to increase public awareness about the benefits of utilizing these sources of energy.

5. Present status of solar energy studies

The Kingdom of Saudi Arabia lies between latitudes 31°N and 17.5°N and longitudes 50°E and 36.6°E. The land elevation varies between 0 and 2600 m above the mean sea level. Complex terrain is found in the southwest region of the Kingdom. The East and the West coasts of the Kingdom are located on the Arabian Gulf and Red Sea, respectively. Mainly two seasons, winter and summer, are observed during the year. The vast open land experiences high intensities of solar radiation and long hours of sunshine duration. There exist a network of 40 stations where global solar radiation (GSR) and sunshine duration has been recorded since 1970 and large number, more than 40, of full meteorological data collection stations where all meteorological parameters have been recorded [22].

A reasonably accurate knowledge of the availability of the solar resource at any place is required by solar engineers, architects, agriculturists, and hydrologists in many applications of solar energy such as solar furnaces, concentrating collectors, and interior illumination of buildings [23]. In other words, solar radiation data are a fundamental input to solar energy applications, such as PV, solar–thermal systems and passive solar design. The data should be reliable and readily available for simulation, design, optimization and performance assessment of various solar technologies at any particular location. Unfortunately, in many developing countries, solar radiation measurements are not easily available because of not being able to afford the measuring equipments and techniques involved. It is, therefore, necessary to develop methods for estimating the solar radiation on the basis of the more readily available meteorological data [24].

Table 2
Some academical research studies conducted on solar energy in Saudi Arabia along with recent centers/programs established.

Institution	Location	Research Study
King Fahad University for Petroleum and Minerals	Dhahran	Heliohydroelectric power generation, possibilities of extraction of magnesium chloride from sea water, estimation of solar insolation isolines in Saudi Arabia, solar energy storage, fuel cells, PVs, solar housing, solar water heating, solar collectors, solar cooling, solar-powered irrigation, hydrogen production, economics of solar energy, electrical infrastructure and control system used for solar energy
King Saud University	Riyadh	Solar water desalination, solar water heating, space heating, crop drying, space cooling, solar housing, solar collectors, solar cooling, solar greenhouse, solar energy education, hydrogen production, biomass
King Faisal University	Al-Hassa	Passive solar cooling
King Abdulaziz University	Jeddah	Solar pump, solar desalination, solar cookers, solar drying, solar collectors, solar stills, participated in R&D work as part of HYSOLAR Program
Taibah University	Medina	Assessment of solar radiation data

Name	Location	Main research branches
Recent Research Centers/Programs		
Center of Research Excellence in Renewable Energy (CoRE-RE), established in 2007 http://corere.kfupm.edu.sa/	King Fahad University for Petroleum and Minerals (KFUPM), Dhahran	Hydrogen, methanol & fuel cell, solar & wind, advanced energy storage branch, electrical infrastructure & control systems, and economics of renewable energy
Solar and Photovoltaic Engineering Research Center http://www.kaust.edu.sa/research/centers/solar.html?submenuheader=0	King Abdullah University of Science and Technology (KAUST), Thuwal	Providing the foundation for innovation in efficient and low-cost disruptive photovoltaic (PV) foundational technologies; nanotechnology for solar energy, advanced molecular PVs, etc.
Sustainable Energy Technologies Program (SET), established in 2010 http://set.ksu.edu.sa/English/Events.aspx	King Saud University, Riyadh	Wind energy, solar energy, hydrogen energy, nuclear energy, desalination and biomass.
Center for Clean Water and Clean Energy at MIT and KFUPM http://engineering.mit.edu/research/labs_centers_programs/kfupm.php	A research and educational partnership between faculty in MIT's Department of Mechanical Engineering and KFUPM. The joint program will lead to the creation of the Center for Clean Water and Clean Energy at MIT and KFUPM.	PV power including silicon and polymer devices and systems, desalination of seawater by advanced membranes and by thermal and solar power, applications of nanotechnology to solar and thermoelectric energy conversion, design and manufacturing of solar power systems and desalination systems.

Modified and updated from Ref. [6].

Practical uses of solar energy in Saudi Arabia include lighting, cooling, cooking, water heating, crop/fruit drying, water desalination, operating irrigation pumps and meteorological stations, and providing road and tunnel lighting, traffic lights, road instruction signals, etc. These practical applications made over a period between 1981 and 2000 have been explained in more detail elsewhere [5,6], while we will focus on the studies conducted by various research centers and investigators in this context. Table 2 indicates some academical research studies conducted on solar energy in Saudi Arabia [6]. As can be seen in this table, various solar energy-related R&D studies have been conducted by a number of Saudi universities, while solar energy projects have also been supported by other governmental and nongovernmental organizations throughout Saudi Arabia.

Studies conducted on estimating the solar radiation and exergy in Saudi Arabia are also listed in Table 3 [24,26,27,29–38,40–42,44,47–52,54] and summarized in the following.

5.1. Solar radiation resources, global solar radiation (GSR) and sunshine duration

Saudi Arabia experiences more than an average GSR value of 2.0 MWh/m^2 yearly on horizontal surface. Fig. 1 illustrates the long-term mean values of sunshine duration and GSR on horizontal surfaces at 41 locations of the country [22]. Depending on these geographical locations, the yearly average minimum and maximum GSR values vary from 1.63 MWh/m^2 to 2.56 MWh/m^2 at Tabuk and Bisha, respectively. It is clear from Fig. 1 that higher values of GSR are observed in the areas of Nejran, Bisha, Al-Sulayyil, etc., located in the Southern most part of Saudi Arabia, while relatively lower values are in the Northern region, such as Hail, Sakaka, and Tabarjal. By comparison, the lower values are much higher than those in other Western and European countries, offering an opportunity to harness the power of the sun for generating electricity. The Eastern and the Western parts of Saudi Arabia also experience higher intensities of global solar radiations and hence should be explored. Fig. 2 shows the seasonal variation values of global solar radiation, which were obtained from 41 locations indicated in Fig. 1 using monthly mean values [22]. As seen from this figure, the lower radiation values are observed in the Winter months, while the higher ones are in the Summer months, with the daily minimum and maximum values of 3.82 kWh/m^2 and 7.09 kWh/m^2 in the months of December and June, respectively. Shaahid and Elhadidy [25] also analyzed hourly wind-speed data recorded at automatic solar radiation and meteorological monitoring station, Dhahran (26°32′N, 50°13′E), Saudi Arabia, to determine monthly wind power. They also compared the wind power with the monthly mean solar radiation energies for the period 1987–1990 while the daily solar radiation varied from 3.46 to 7.43 kWh/m^2 and the yearly annual solar potential per unit area of the earth surface was 2.03 MWh/m^2.

A survey of the existing literature on the issue related to Saudi Arabia reveals mainly two distinctive approaches for estimating the global solar radiation, namely (i) the first one is related to utilizing various empirical models (or correlations) developed in order to estimate the solar radiation and (ii) the second one has more recently been introduced, while includes artificial intelligence techniques such as artificial neural networks (ANNs). This ANN technique has been widely accepted as a computational approach offering an alternative way to modeling complex mappings.

5.1.1. Estimation of solar radiation using geostatistical technique

The term geostatistics is widely applied to a set of data, which accounts for spatial continuity using statistics, while it is a useful

Table 3
Studies conducted on estimating the solar radiation and exergy in Saudi Arabia [24,26,27,29,30–38,40–42,44,47–52,54].

Investigators	Year published	Location	Estimating the solar radiation			Solar exergy	Remarks
			Geostatistical technique	Empirical correlations	Artificial intelligence techniques		
Rehman and Ghori [26]	2000	41 various locations in Saudi Arabia	√				The spatial variation of GSR data was studied, while the mean percent deviations between the measured and estimated values varied between 0.5% and 1.7%.
Sabtagh et al. [27]	1973	Riyadh		√			Correlation of solar radiation and sunshine duration was developed using data from three Stations.
Sabtagh et al. [29]	1977	Saudi Arabia and other countries		√			The daily GSR at various places in Egypt, Kuwait, Lebanon, Sudan and Saudi Arabia was estimated using sunshine hours, maximum air temperature, latitude and relative humidity.
Bakhsh et al. [30]	1985	Dhahran		√			A simple correlation for estimating the hourly ratio of diffuse to total radiation received by a horizontal surface was developed. They compared their correlation developed and compared with the existing models for hourly diffuse radiation fraction.
Bahel et al. [31]	1986	11 cities in Saudi Arabia		√			A linear correlation between GSR and sunshine duration was developed.
Abdelrahman and Elhadidy [32]	1986	Dhahran		√			Three models for calculating the total radiation on inclined surfaces were developed and compared based on the measurements over the period March 1984 to April 1985.
Al Mahdi et al. [33]	1992	Riyadh, Abu Dhabi, Bahrain, Doha and Kuwait		√			A statistical assessment of the accuracy of 12 solar radiation models was made. Of these, 6 were the regression type, in which the measured global radiation was correlated with the sunshine hours and other meteorological parameters. The other 6 models were based on the calculation of clear sky radiation and the effects of cloud amount and sky transmittance.
Zuhairy and Sayigh [34]	1995	Riyadh, Jeddah, Dhahran and Taif		√			A mathematical model was used to generate the hourly data for the total solar radiation on a horizontal surface using the hourly recorded visibility data for a period from 1970 to 1989. The accuracy was above 90% representative.
Rehman and Halawani [35]	1997	52 cities in 11 countries		√			The empirical correlation given in Eq. (1) was used to estimate monthly mean daily GSR in 52 cities.
Rehman [36]	1998	41 various locations in Saudi Arabia		√			A comparison between models developed by the present authors and 16 other models for different geographical and varied meteorological conditions was made.

Table 3 (*Continued*)

Investigators	Year published	Location	Estimating the solar radiation			Solar exergy	Remarks
			Geostatistical technique	Empirical correlations	Artificial intelligence techniques		
Al-Ayed et al. [37]	1998	Riyadh		√			The relationship of the daily and monthly variation of the fraction of the diffuse solar irradiation to extraterrestrial (H_d/H_0) and the clearness index (H/H_0) was developed.
Rehman [38]	1999	41 various locations in Saudi Arabia		√			The models of Eq. (3) and Khogali et al. [34] given in Eq. (4) presented the best estimates of H.
Aksakal and Rehman [40]	1999	Near Dhahran		√			GSR values were estimated using two empirical formulas. The agreement between the measured and estimated solar radiation values was satisfactory.
Benghanem and Joraid [41]	2007	Medina site		√			Correlations between diffuse and global irradiation and sunshine duration were developed using a database available at the National Renewable Energy Laboratory (NREL) website for 5 years since 1998 until 2002.
Maghrabi [42]	2009	Tabouk		√			A multiple regression relation based on 9 years of solar radiation data to estimate the GSR for Tabouk using five meteorological variables was developed
El-Sebaii et al. [44]	2009	Jeddah		√			Various correlations were developed based on the fraction (H/H_0), sunshine fraction (S/S_0) and other meteorological parameters, such as mean T_a, maximum $T_{a,\max}$ and minimum $T_{a,\min}$ ambient temperatures as well as humidity R_h and cloud cover C_w using the whole date over the period 1996–2006.
El-Sebaii et al. [24]	2010	Jeddah		√			The same meteorological variables given in Ref. [39] were used based on the period 1996–2007, while the diffuse fraction (H_d/H) and diffuse transmittance (H_d/H_0) were correlated.
Mohandes et al. [47]	1998	41 various locations in Saudi Arabia			√		There was a relatively good agreement between the observed and predicted values and hence the method introduced was viable.
Mohandes et al. [48]	2000	41 various locations in Saudi Arabia			√		The radial basis functions technique was used to estimate monthly mean daily values of solar radiation falling on horizontal surfaces.
Rehman and Mohandes [49]	2008	Abha			√		The data for 240 days in 2002 were used to test the performance of the ANN system, while it was concluded that neural networks were well capable of estimating diffuse solar radiation from temperature and relative humidity.

Table 3 (*Continued*)

Investigators	Year published	Location	Estimating the solar radiation			Solar exergy	Remarks
			Geostatistical technique	Empirical correlations	Artificial intelligence techniques		
Rehman and Mohandes [50]	2009	Abha			✓		The analysis was based on the measured data between 1998 and 2002 for training the neural networks and the remaining 250 days' data from 2002 as testing data, while the data for 250 days in the year 2002 was used to test the performance of the ANN system.
Benghanem et al. [51]	2009	Al-Madinah			✓		Six various ANN models were developed to estimate and model daily global solar. Radiation, while the data were available from 1998 to 2002 at the NREL website.
Benghanem and Mellit [52]	2011	Al-Madinah			✓		The ANN models reported in Ref. [24] was applied for estimating the sizing of a stand-alone PV system in order to show the effectiveness of the developed RBF-model.
Hepbasli and Alsuhaibani [54]	2010	Northeastern Saudi Arabia				✓	The ratios of solar radiation exergy to solar radiation energy (exergy-to-energy ratio) were obtained to be on average 0.933 for both approaches of Petela [51,52] and Spanner [53] and 0.950 for Jefer's approach [54] at outside air temperatures between 16.18 and 33.01 °C.

tool for evaluating, estimating, and studying spatial characteristics of a regionalized variable. The technique consists of five steps, namely: (i) data collection, (ii) univariate analysis, (iii) experimental variogram calculations and model fitting, (iv) estimation using kriging, and (v) plotting contour maps. In this regard, Rehman and Ghori [26] utilized the geostatistical technique to estimate solar radiation in Saudi Arabia by studying the spatial variation of GSR data. Variogram models were fitted to measured variograms for each month of the year. These values were used to plot the contour maps of solar radiation for each month of the year. To test the performance of the technique, estimates were obtained at the 41 known locations by systematically excluding one of these points from the known data. Kriged estimates were computed for each point on a regular grid covering the whole of Saudi Arabia. The whole area was divided into 30 × 50 grid points, thus providing estimates every 33 km on longitude and 55 km on latitude. These kriged estimates of GSR on horizontal surface and extraterrestrial radiation (H/H_0) were used to plot a contour map for each month. Fig. 3 illustrates contour maps where spatial variation of ratios of estimated and extraterrestrial radiation over Saudi Arabia in the months of January and February is indicated [26]. In general, the radiation maps indicate clearly the locations of highs and lows over the year. The seasonal trend, with lower values of H/H_0 in winter months (December–March) and higher in summer months (April–November), is also depicted in these maps. Based on the results obtained, the difference between the measured and estimated values using this technique was minimal. The mean deviation between the measured and estimated values varied from a maximum of 0.0037 in January to a minimum of 0.0013 in March and October, whereas the mean percent deviations were found to vary between 0.5% and 1.7%.

5.1.2. Estimation of solar radiation using empirical correlations

As far as other studies on estimating the solar radiation using empirical correlations in Saudi Arabia are concerned, Sabtagh et al. [27] used the average hours per month of sunshine $\bar{S}$ using data from three Stations as follows:

$$\bar{H} = \bar{S}(a + b\,Ln\,m) \tag{1}$$

where a and b are correlation coefficients, while m = 1,2,3,4,5,6 [28].

Sabbagh et al. [29] estimated the daily GSR at various places in Egypt, Kuwait, Lebanon, Sudan and Saudi Arabia using sunshine hours, maximum air temperature, latitude and relative humidity as follows:

$$H = 1.53\,K\,\exp\left[L\left(\frac{S}{12} - \frac{R_h^{0.333}}{100} - \frac{1}{T_{\max}}\right)\right] \tag{2}$$

where K is the geographical factor, L_l is the latitude of location, S is the monthly mean sunshine duration, R_h is relative humidity and $T_{\max}$ is the monthly mean of maximum air temperature.

Bakhsh et al. [30] presented a simple correlation for estimating the hourly ratio of diffuse to total radiation received by a horizontal surface using insolation measurements made at Dhahran, Saudi Arabia. They compared their correlation developed with the existing models for hourly diffuse radiation fraction and obtained a good agreement.

Bahel et al. [31] used an Eppley Normal Incidence Pyrheliometer to measure the duration of the bright sunshine for Dhahran between May 1979 and July 1985, while they derived a linear correlation between the monthly average daily GSR and the sunshine duration. They also used their correlation to estimate the GSR for 11 cities in Saudi Arabia and found a maximum of 10% difference

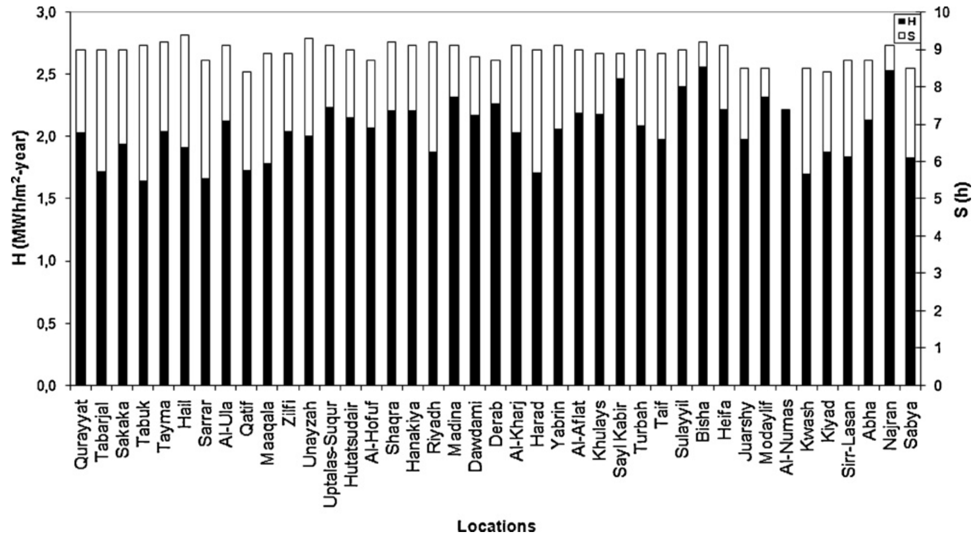


Fig. 1. Long-term mean values of sunshine duration (S) and global solar radiation (H) on horizontal surfaces in various locations of Saudi Arabia. Modified from Ref. [22].

between the measured and estimated values of H for Qatif. Their correlation is as follows:

$$\frac{H}{H_0} = 0.175 + 0.552\left(\frac{S}{S_0}\right) \tag{3}$$

Abdelrahman and Elhadidy [32] used the total radiation data measured at Dhahran, Saudi Arabia, on a surface inclined at 26° from the horizontal for the period March 1984 to April 1985 to test three models (one isotropic model and two anisotropic models) for calculation of total radiation on inclined surfaces. They also used the total and diffuse radiation measured on a horizontal surface to make calculations with these models, while they compared the models on the basis of the statistical error tests using the root mean square error (RMSE) and the mean bias error (MBE). The RMSE varied between 0.399% and 5.578%. It was concluded that for hot-arid areas, the isotropic model was more accurate for tilt angle values around the latitude of the location.

Al Mahdi et al. [33] made a statistical assessment of the accuracy of 12 solar radiation models for five meteorological stations in Abu Dhabi, Bahrain, Doha, Kuwait and Riyadh using RMSE and MBE. Of these, 6 were the regression type, in which the measured global radiation was correlated with the sunshine hours and other meteorological parameters. The other 6 models were based on the calculation of clear sky radiation and the effects of cloud amount and sky transmittance. The obtained results indicated some inconsistency of published data for Abu Dhabi, Bahrain and Doha stations, while using Kuwait and Riyadh stations as a basis for the assessment, two models were recommended for estimating the monthly average daily and hourly global radiation for these places.

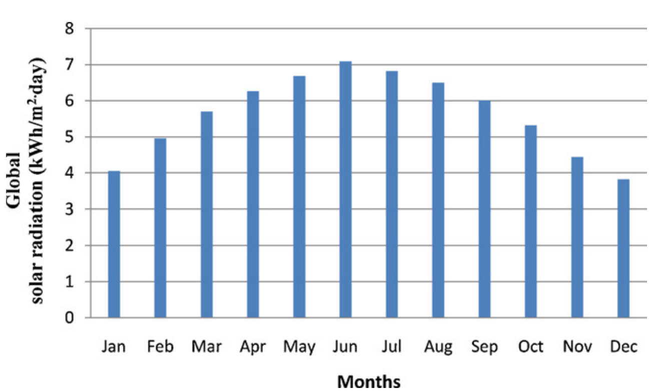


Fig. 2. Seasonal variation of global solar radiation over Saudi Arabia. Modified from Ref. [22].

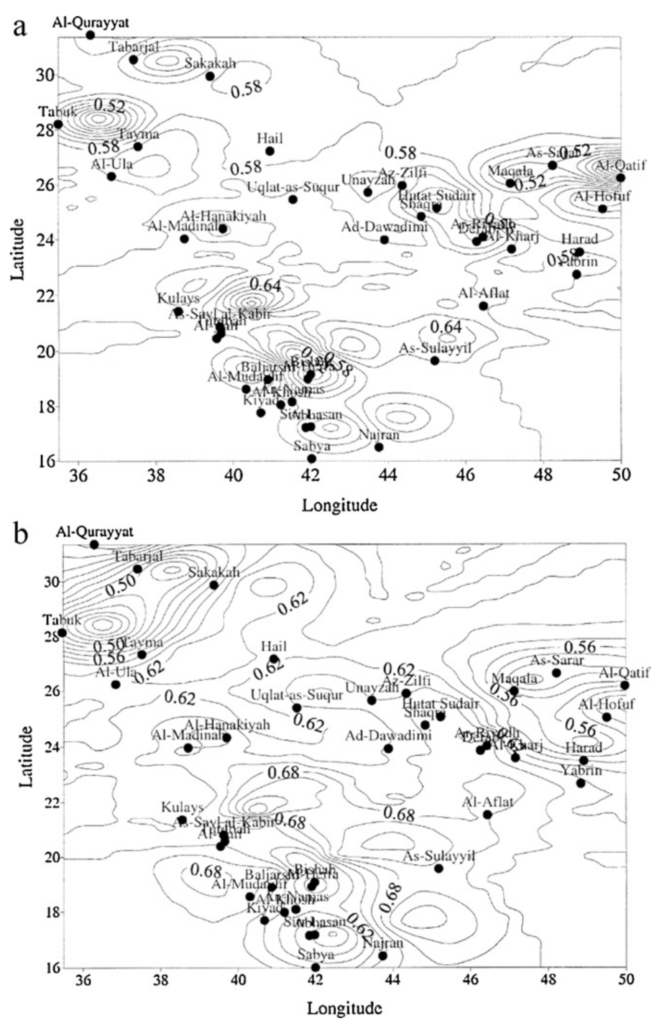


Fig. 3. Contour maps showing spatial variation of ratios of estimated and extraterrestrial radiation over Saudi Arabia in January (a) and February (b) [26].

Zuhairy and Sayigh [34] used a mathematical model to generate the hourly data for the total solar radiation on a horizontal surface, while their generated data were based on the hourly recorded visibility data for a period from 1970 to 1989. They applied the model year technique for modeling the 20 years of hourly data of solar radiation into one statistically representative year. A model year of hourly data was then generated for the beam and diffuse components of solar radiation on a horizontal surface. Similarly, a model year of hourly data was also generated for the total solar radiation on tilted surfaces with different orientations with its beam, diffuse and reflected components. A simple methodology was proposed to calculate the solar radiation on vertical surfaces based on a solar impact factor. Monthly means and daily totals of hourly sums for each month of the year were discussed while the hourly data of solar radiation for a typical day for each month of the year were given. The data generated covered the four climatic zones of Saudi Arabia, the hot-dry (Riyadh), the warm-humid (Jeddah), the maritime inland desert climate (Dhahran) and the upland climate zone (Taif). The accuracy of the results was found to be above 90% representative.

Rehman and Halawani [35] made a comparison between the observed and estimated values of GSR on horizontal surfaces obtained from their linear Angstrom type of correlation developed previously for 52 cities spread in 11 countries; two in India, five in Egypt, four in Sri Lanka, six in Spain, three in Zimbabwe, five in Yemen, 14 in Sudan, three in Italy, six in Zambia, one in Hong Kong and three in Malaysia. They utilized the mean bias error (MBE), mean absolute bias error (MABE), root mean square error (RMSE), and mean percent error (MPE) to test the performance of the correlation developed. Their model was capable of giving estimates within an acceptable mean percent error of 5% and less for 33% of cities and between 5 and 10% for 50% of cities.

Rehman [36] made a comparison between models developed by the present authors and 16 other models for different geographical and varied meteorological conditions. He tested the performance of the models developed using the mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE), and mean absolute bias error (MABE). The calculations of these models were based on monthly mean, measured daily and estimated values of total solar radiation for 41 locations in Saudi Arabia. It was reported that the latitude, longitude, altitude, and sunshine-duration-dependent model given in Eq. (4) produced the best estimates for global solar radiation.

$$\frac{H}{H_0} = -0.3346 + 0.558\cos\phi + 0.20\cos\psi + 0.006\,h + 0.3809\left(\frac{S}{S_0}\right) \quad (4)$$

The second- and third-best estimates were obtained from his linear model and other models given in Eqs. (3) and (4), respectively, as also reported elsewhere [37].

$$\frac{H}{H_0} = 0.3465 + 0.352\left(\frac{S}{S_0}\right) \quad (5)$$

$$\frac{H}{H_0} = 0.35 + 0.36\left(\frac{S}{S_0}\right) \quad (6)$$

The frequency distribution analysis indicated higher frequencies in lower error intervals for the models of Eqs. (4) and (5). Hence, these models were recommended for estimating H in Saudi Arabia.

Al-Ayed et al. [37] determined the regression coefficient of the well-known Angstrom correlation for Riyadh, Saudi Arabia. They developed the relationship of the daily and monthly variation of the fraction of the diffuse solar irradiation to extraterrestrial (H_d/H_0) and the clearness index (H/H_0). The variation of the values of the average daily GSR against the month of the year was reported. The daily diffused ratio and the daily clearness index were also shown as a function of the month of the year.

Rehman [38] utilized monthly mean daily values of global solar-radiation and sunshine duration at 41 locations in Saudi Arabia, while he developed an empirical correlation for estimating the GSR at locations where it was not measured. He also compared his present correlation with other models developed under different geographical and varied meteorological conditions. In the comparisons, standard statistical tests, namely MBE, RMSE, MPE and MABE tests. The errors were calculated using monthly mean daily measured and estimated values of GSR at all 41 locations. The present model of Eq. (3) with MBE = −0.015, RMSE = 0.595, MPE = 10.02% and MABE = 0.533 presented the best estimates of H. The second best estimates were obtained from the model of Khogali et al. [39] given in Eq. (4), with MBE = 0.067, RMSE = 0.593, MPE = 10.20% and MABE = 0.533. Hence, this correlation should be used for the estimation of global solar-radiation in Saudi Arabia.

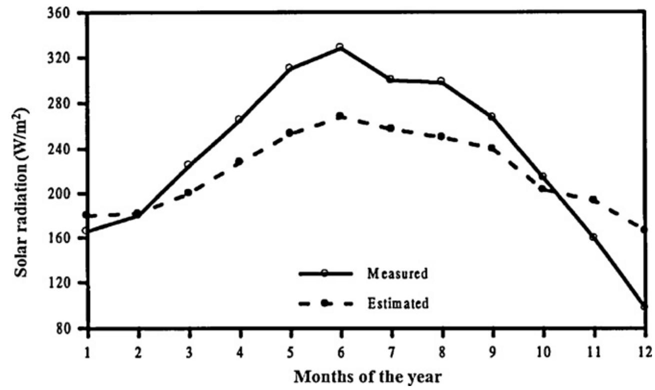


Fig. 4. Comparison between measured and estimated monthly mean global solar radiation on horizontal surfaces [40].

Aksakal and Rehman [40] performed solar radiation measurements based on the real time high-resolution measurements (i.e., from the 1-min averaged measurements for one complete year), in the Arabian Gulf Coast near the city of Dhahran. They obtained the highest measured daily, and monthly mean solar radiation values of 240 and 217 W/m^2, respectively, while they observed the highest 1-min averaged solar radiation values up to 1183 W/m^2 in the summer season, from May-September. The highest hourly solar radiation value was recorded as 1053 W/m^2 in the middle of June. Besides the GSR measurements, the main observed meteorological parameters considered were temperature, pressure, wind speed, precipitation, and relative humidity. Fig. 4 illustrates the estimated monthly GSR values using the empirical formula given below [40]:

$$H_0 = (1.75 - 0.458\phi)\left(\frac{20Z}{1 + 0.1\phi} + \psi\cos\phi\right) \quad (7)$$

where ϕ is the latitude of the monitoring station, Z is the maximum possible daylight hours and ψ is the monthly averaged relative humidity factor.

As seen in Fig. 4, the agreement between the measured and estimated solar radiation values was satisfactory. The monthly GSR values reach their peak values during the summer "May–July" and low values during the winter "November–January". It was also reported that somehow the cloud coverage and precipitation amount should be considered and incorporated in the empirical formula in order to minimize the differences between the measured values and estimated solar radiation.

Benghanem and Joraid [41] developed the correlation between diffuse and global irradiation and sunshine duration in Medina site, in Saudi Arabia, while they used a database available at the NREL website for 5 years since 1998 until 2002. A typical meteorological year was built from this database. The correlation connecting diffuse irradiation with both clearness index and sunshine duration was found to be applicable in Medina site, while a linear correlation between ambient temperature and global irradiation

data was obtained from sunrise until midday with a good agreement.

For Medina site, the correlations between global irradiation and sunshine duration for winter and summer with coefficients of correlation (R) of 0.79 and 0.78 are as follows, respectively.

$$K_t = \frac{H}{H_0} = -0.39 + 1.28\left(\frac{SS}{SS_0}\right) \quad (8)$$

$$K_t = \frac{H}{H_0} = -0.38 + 1.33\left(\frac{SS}{SS_0}\right) \quad (9)$$

where K_t is the clearness index, H is the global irradiation on horizontal surface and SS is the sunshine duration [41].

For Medina site, the correlations between diffuse irradiation and global irradiation for winter and summer with coefficients of correlation (R) of 0.85 and 0.76 are as follows, respectively.

$$\frac{H_D}{H} = 1.20 - 1.47\left(\frac{H_G}{H_0}\right) \quad (10)$$

$$\left(\frac{H_D}{H}\right) = 1.13 - 1.32\left(\frac{H_G}{H_0}\right) \quad (11)$$

where H_D is the diffuse irradiation on horizontal surface [41].

Benghanem and Joraid [41] also reported that Eqs. (8) and (9) had the same correlation coefficient $R \approx 0.79$ and practically the same coefficients of linear regression. This meant that the relation between global irradiation and sunshine duration depended on the season in Medina site. Eq. (10) had the best correlation coefficient than Eq. (11) and hence the effect of the diffuse irradiation was more important in winter than in summer in Medina site.

Maghrabi [42] developed a multiple regression relation based on 9 years of solar radiation data to estimate the GSR for Tabouk using five meteorological variables. These included the mean monthly daily fraction of possible sunshine hours (S/S_0), air temperature (T_a), atmospheric pressure (P_{at}), perceptible water vapor (PWV) and relative humidity (R_h). The multiple regression developed between the GSR (H) and these parameters is given below:

$$H = 163.01 - 1.04\left(\frac{S}{S_0}\right) + 0.12T_a - 0.21P_{at} - 1.06PWV - 0.03R_h \quad (12)$$

The estimated global radiation from the model was compared with the measured values using MBE, R, RMSE and MPE, while the t-statistics were also applied as another indication of suitability. The statistical test values calculated are: $R = 0.99$, $\text{MBE} = -14 \times 10^{-4}\,\text{kWh/m}^2$, $\text{RMSE} = 0.10\,\text{kWh/m}^2$, and $\text{MPE} = -0.03\%$. It was reported hat the model developed in this work was applicable for estimating, with great accuracy. The monthly mean daily global radiation at any site having similar conditions to those found in Tabouk. 29 regression models available in the literature were also used to estimate the GSR data for Tabouk. The selected models were different in terms of the variables they used and in the number of the variables they contained. The models were compared on the basis of the statistical errors considered above. Apart from Abdall's model [43], which showed a reasonable estimate ($\text{MPE} = -2.04\%$, $\text{MBE} = -0.22\,\text{kWh/m}^2$, and $\text{RMSE} = 0.59\,\text{kWh/m}^2$), all the models under or overestimated the measured solar radiation values. According to the statistical results, the model of Abdall showed the prediction closest to those estimated using the developed model. These statistical parameters indicated that the model, with these selected variables, could be used to estimate the monthly GSR with fairly high accuracy in Tabouk and in other places having similar conditions.

El-Sebaii et al. [44] analyzed and calculated the monthly average daily values of the meteorological data for Jeddah in Saudi Arabia. Their correlations developed were based on the fraction (H/H_0), sunshine fraction (S/S_0) and other meteorological parameters, such as mean T_a, maximum $T_{a,\max}$ and minimum $T_{a,\min}$ ambient temperatures as well as humidity R_h and cloud cover C_w, as listed below with coefficients of determination (R^2) of 0.974, 0.985, 0.986,0.963, 0.974 and 0.996, respectively.

$$\frac{H}{H_0} = -2.81 - 3.78\left(\frac{S}{S_0}\right) \quad (13)$$

$$\frac{H}{H_0} = -1.92 + 2.60\left(\frac{S}{S_0}\right) + 0.006T_a \quad (14)$$

$$\frac{H}{H_0} = -1.62 + 2.24\left(\frac{S}{S_0}\right) + 0.332R_h \quad (15)$$

$$\frac{H}{H_0} = 0.139 - 0.003T + 0.896R_h \quad (16)$$

$$\frac{H}{H_0} = -2.76 + 3.72\left(\frac{S}{S_0}\right) + 0.001C_w \quad (17)$$

$$\frac{H}{H_0} = -0.08 + 0.21(T_{a,\max} - T_{a,\min})^{0.5} - 0.012C_w \quad (18)$$

The whole data over the period 1996–2006 were divided into two sets. The sub-data set I (1996–2004) were employed to develop empirical correlations between the monthly average of daily GSR fraction (H/H_0) and various meteorological parameters. The non linear Angström type model developed by Sen [45] and the trigonometric function model proposed by Bulut and Büyükalaca [46] were also evaluated. The sub-data set II (2005, 2006) were then used to evaluate the derived correlations. Comparisons between measured and calculated values of H were made. The models proposed by Sen [45], and Bulut and Büyükalaca [46] satisfactorily described the horizontal GSR for Jeddah. Comparisons between measured and calculated values of H indicated that first order correlations between H/H_0, S/S_0 and combinations of the other climatic parameters could be used for estimating H with relative percentage errors for a single month less than 15%. All the proposed correlations were found to be able to predict the annual average of daily GSR with excellent accuracy. Therefore, the long term performance of solar energy devices could be estimated.

El-Sebaii et al. [24] analyzed the measured data of global and diffuse solar radiation on a horizontal surface, the number of bright sunshine hours, mean daily ambient temperature, maximum and minimum ambient temperatures, relative humidity and amount of cloud cover for Jeddah, Saudi Arabia, during the period (1996–2007). They calculated the monthly averages of daily values for these meteorological variables and divided the data into two sets. The sub-data set I (1996–2004) were employed to develop empirical correlations between (H/H_0) and the various weather parameters, while the sub-data set II (2005–2007) were used to evaluate the derived correlations. The total solar radiation on horizontal surfaces was also separated into the beam and diffuses components. In order to develop empirical correlations for calculating the monthly average daily diffuse radiation incident on a horizontal surface, the diffuse fraction (H_d/H) and diffuse transmittance (H_d/H_0) were correlated to first, second and third order correlations of the clearness index K_t and the relative number of sunshine hours (S/S_0). It was reported that the second and third order correlations did not improve the accuracy of estimation of H_d and hence the following correlations were obtained for Jeddah with R^2 values of 0.956, 0.899, 0.908 and 0.961, respectively.

$$\frac{H_d}{H} = 4.618 - 6.269K_t \quad (19)$$

$$\frac{H_d}{H} = 5.488 - 5.672\left(\frac{S}{S_0}\right) \quad (20)$$

$$\frac{H_d}{H_0} = 3.542 - 3.664\left(\frac{S}{S_0}\right) \quad (21)$$

$$\frac{H_d}{H_0} = 2.973 - 4.037K_t \quad (22)$$

H_d/H and H_d/H_0 were also correlated to first and second order correlations of the K_t and S/S_0 combination. It was obtained that the second order correlations between H_d/H or H_d/H_0 and K_t and S/S_0 combination did not improve the accuracy of estimation of H_d. The following correlations were found to fit the measured data of H_d with R^2 values of 0.963 and 0.965, respectively [24].

$$\frac{H_d}{H} = 4.609 - 6.318K_t + 0.047\left(\frac{S}{S_0}\right) \quad (23)$$

$$\frac{H_d}{H} = 3.002 - 3.882K_t - 0.150\left(\frac{S}{S_0}\right) \quad (24)$$

5.1.3. Estimation of solar radiation using artificial intelligence techniques

On the base of the studies conducted on artificial intelligence techniques, Mohandes et al. [47] introduced neural networks technique to model and estimate global solar radiation. They used the available data from 31 locations to train the neural networks and the data from other 10 locations to test. The testing data were not utilized in the modeling to give an indication of the performance of the system in unknown locations. It was concluded that there was a relatively good agreement between the observed and predicted values and hence the method introduced was viable.

Mohandes et al. [48] also utilized the radial basis functions technique for the estimation of monthly mean daily values of solar radiation falling on horizontal surfaces, while they compared its performance with that of the multilayer perceptrons network and a classical regression model. Solar radiation data from 41 stations that were spread over Saudi Arabia were used. The solar radiation data from 31 and 10 locations were used to train the neural networks and to test he estimated values. The testing data were not used in the modeling or training of the networks to give an indication of the performance of the system at unknown locations. It was concluded it demonstrated the concept although their data sample was relatively small, representing only 1 year from each of 32 locations, Adding data would further improve the models' performances due to the ANNs methods depend on learning from examples.

Rehman and Mohandes [49] used the values for the measured daily mean air temperature and relative humidity between 1998 and 2001 for Abha city in Saudi Arabia to predict diffuse fraction of solar radiation in future time domain using the ANN method. They estimated the diffuse solar radiation using four combinations of data sets, namely (i) day of the year and daily maximum air temperature as inputs and diffuse solar radiation as output, (ii) day of the year and daily minimum air temperature as inputs and diffuse solar radiation as output, (iii) day of the year and daily mean air temperature as inputs and diffuse solar radiation as output, and (iv) time day of the year, daily mean air temperature, and relative humidity as inputs and diffuse solar radiation as output. They used data for 240 days in the year 2002 to test the performance of the ANN system. They concluded that neural networks were well capable of estimating diffuse solar radiation from temperature and relative humidity, while these could be used to estimate diffuse solar radiation for locations where only temperature and humidity data were available.

The results indicated that using the relative humidity along with daily mean temperature outperformed the other cases with absolute mean percentage error of 4.49%. The absolute mean percentage error for the case when only day of the year and mean temperature were used as inputs was 11.8% while when maximum temperature was used instead of mean temperature was 10.3%. Rehman and Mohandes [50] also used the same ANN methodology explained given in Ref. [49], while their analysis was based on the measured data between 1998 and 2002 for training the neural networks and the remaining 250 days' data from 2002 as testing data. They used data for 250 days in the year 2002 to test the performance of the ANN system. They concluded that neural networks were well capable of estimating diffuse solar radiation from temperature and relative humidity, while these could be used to estimate diffuse solar radiation for locations where only temperature and humidity data were available.

Benghanem et al. [51] developed six ANN-models for estimating of solar radiation in Al-Madinah, Saudi Arabia, while they used different combination as inputs: the air temperature, relative humidity, sunshine duration and the day of year. They compared measured daily GSR with those obtained by the different designed ANN-models. For each model, the output was the daily global solar radiation.

In order to show the potential of the proposed ANN-models, a comparative study between designed ANN-models and conventional correlation models was made. Therefore, the models developed for Al-Madinah with R values of 97.28%, 97.48%, 89.50% and 86.59%, are as follows, respectively [51]:

$$\frac{H}{H_0} = -0.3824 + 0.2786\left(\frac{S}{S_0}\right) \quad (25)$$

$$\frac{H}{H_0} = 0.1166 - 0.2202\left(\frac{S}{S_0}\right) + 1.0723\left(\frac{S}{S_0}\right)^2 \quad (26)$$

$$\frac{H}{H_0} = 0.6369 + 0.037\left(\frac{T_a}{T_{a,\max}}\right) \quad (27)$$

$$\frac{H}{H_0} = 0.7556 - 0.1353\left(\frac{R_h}{R_{h,\max}}\right) \quad (28)$$

The ANN models with R values of 97.44%, 97.65%, 97.54%, 89.20%, 87.00% and 88.99% are developed are as follows [51]:

$$H = \tilde{f}(t, S) \quad (29)$$

$$H = \tilde{f}(t, S, T) \quad (30)$$

$$H = \tilde{f}(t, S, T, R_h) \quad (31)$$

$$H = \tilde{f}(t, T) \quad (32)$$

$$H = \tilde{f}(t, R_h) \quad (33)$$

$$H = \tilde{f}(t, T, R_h) \quad (34)$$

Comparing the different ANN-models (Eqs. (29)–(34)) with conventional regression models (Eqs. (25)–(27)) indicated that the second model, with S and T as inputs presented better accurate results than others ANN-models done by Benghanem et al. [51]. All models also indicated low MBE values. For most of the models, the MBE values were comparable to the experimental error for the ANN-models proposed by their research and it could not be considered as decisive for the prevalence of any one of the models.

Obtained results also indicated that the second ANN-model (ANN-ST model) had better accurate results than the others ANN-models. However, for each developed ANN-models, R was grater than 97%. Only one hidden layer was sufficient to estimate the daily GSR from other parameters, and the number of neurons in the hidden layer was arranged between three and five neurons. It was reported that the sunshine duration played very important role for obtaining high accurate results, while the ANN-models which used only the air temperature and day of year as inputs could give a good results to the others models from the R point view.

Benghanem and Mellit [52] also used radial basis function (RBF) network to model and predict the daily GSR data using other

meteorological data such as air temperature, sunshine duration, and relative humidity. These data were recorded over a period between 1998 and 2002 at Al-Madinah (Saudi Arabia) by the NREL. Four RBF-models have been developed for predicting the daily global solar radiation. The measured daily GSR was compared with those estimated using different designed RBF-models. An application for estimating the sizing of a stand-alone PV system at Al-Maidinah was also presented in order to show the effectiveness of the developed RBF-model. It was concluded that the predicted data by the RBF were very suitable for estimating the sizing curve of a stand-alone PV system at Al-Madinah city.

5.2. Estimating the exergetic solar radiation values of some Saudi Arabian regions

The conversion of solar energy into useful energy like mechanical or electrical energy, does not play an important role in the energy budget of most countries yet. But this energy conversion will become more important in future because of its environmentally perfect standing and it is important to have the thermodynamic tools ready for action when the demand increases. Given a fixed environment, exergy is the fraction of the incoming energy, which is fully convertible into mechanical or electrical energy. Mechanical and electrical energy are completely exergy, they are fully convertible in all other energy types. Solar energy is not fully convertible because of its entropy content and thus its exergy content is less than 100%. Thus the energetic conversion efficiency of a solar conversion device will not be one, even if there were an ideal, fully reversible conversion. The exergy content of solar radiation reaching the surface of the earth is between 50% and 80% of its energy flux, depending on the atmospheric conditions [53].

As far as studies on calculating the solar exergy of Saudi Arabian regions are concerned, only one study conducted by Hepbasli and Alsuhaibani [54] has appeared in the open literature to the best of the authors' knowledge. In this context, they comprehensively reviewed various solar exergy models used in solar energy-related applications, and determined the solar exergetic values for some regions of Saudi Arabia and Turkey, which were taken as two illustrative examples, to which various models were applied and compared. The data used in the analysis related to Saudi Arabia were taken from Sahin et al. [55], who reported the experimental values obtained from the measurements on the shoreline of the Arabian Gulf in northeastern Saudi Arabia, near Dhahran. The ratios of solar radiation exergy to solar radiation energy (exergy-to-energy ratio) for northeastern Saudi Arabia were obtained to be on average 0.933 for both approaches of Petela [56,57] and Spanner [58] and 0.950 for Jefer's approach [59] at outside air temperatures between 16.18 and 33.01 °C. The solar radiation exergy values for northeastern Saudi Arabia are obtained to vary between 153.72 and 306.29 W/m^2 from January to June for both approaches of Petela and Spanner, and from 156.37 to 311.86 for Jefer's approach at outside air temperatures between 16.18 and 33.01 °C. These values were calculated to be in the range of 286.24–91.62 W/m^2 and 291.47–93.21 from July to December for the above mentioned approaches, respectively [54].

5.3. Other solar energy-related research studies conducted

In the following, studies conducted on solar collectors [60–62] and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) clear-sky model for producing solar-radiation [63], solar PV systems [3,22,64–75], solar stills [76,77], solar-powered irrigation [78,79], solar energy-related greenhouses [80,82], solar hydrogen [13,83–93], solar water desalination [5,15–17,94–98] and solar energy education [99–106] are briefly presented.

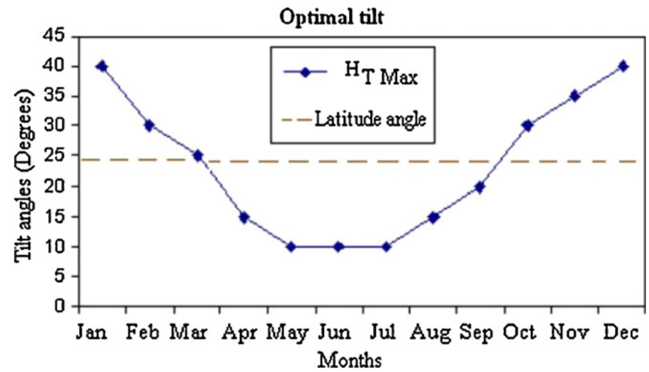


Fig. 5. Optimum average tilt angle for each month of the year at Madinah site [62].

5.3.1. Solar collectors and ASHRAE clear-sky model

Samanta and AI Balushi [60] reported that most solar collectors commonly used were of the flat-plate type. They proposed a novel type of solar collector, the so-called spherical collector, which consisted of a stationary spherical body with a cover and an absorbing surface. The sun could be effectively tracked through this collector, without any actual mechanical movement. The annual average of the daily incident solar irradiation on spherical collector was about 21% higher than that on the fiat-plate one for the two locations in the Gulf Cooperative Council countries considered in their study. Both daily and hourly variations of incident radiation on such a spherical solar collector were computed on the basis of available data, while the results obtained were compared to that on an equivalent fiat-plate collector for different angles of tilt and latitude. It was concluded that the results would be very beneficial to everyone dealing with the design and performance evaluation of spherical collectors, while the issues of construction and operation of such collectors should be investigated in more detail.

The orientation and tilt angle with horizontal of a solar collector highly influence its performance. Therefore in the design, simulation and operation of solar collectors, it is very essential to know the optimum tilt angle. Optimum tilt angle is applied to a variety of systems, such as flat or parabolic collectors, PV-systems, solar houses and solar greenhouses installed in a fixed position. In addition to these, it is crucial in the determination of the lengths of the shading elements to be placed above the windows in buildings as well as in the right selection of the angles of these elements if they are located angular [61]. Benghanem [62] analyzed the optimal choice of the tilt angle for the solar panel in order to collect the maximum solar irradiation. In the analysis, the collector surface was assumed to be facing towards equator, while the measured values of daily global and diffuse solar radiation on a horizontal surface were utilized. Fig. 5 indicates the tilt angles for each month of the year when the collector panel was titled at the optimum angle at Madinah site [62]. The seasonal average was calculated by finding the average value of the tilt angle for each season and the implementation of this required the collector tilt to be changed four times a year. The tilt should be 17°, 12°, 28° and 37° in the seasons of spring, summer, autumn and winter, respectively. The yearly average tilt was calculated by finding the average value of the tilt angles for all months of the year. The yearly average tilt was found to be 23.5°, which resulted in a fixed tilt throughout the year, nearly corresponding to the latitude of Madinah site (24.5°). It was concluded that annual optimum tilt angle was approximately equal to latitude of the location, while the loss in the amount of collected energy when using the yearly average fixed angle was around 8% compared to the monthly optimum angle of tilt.

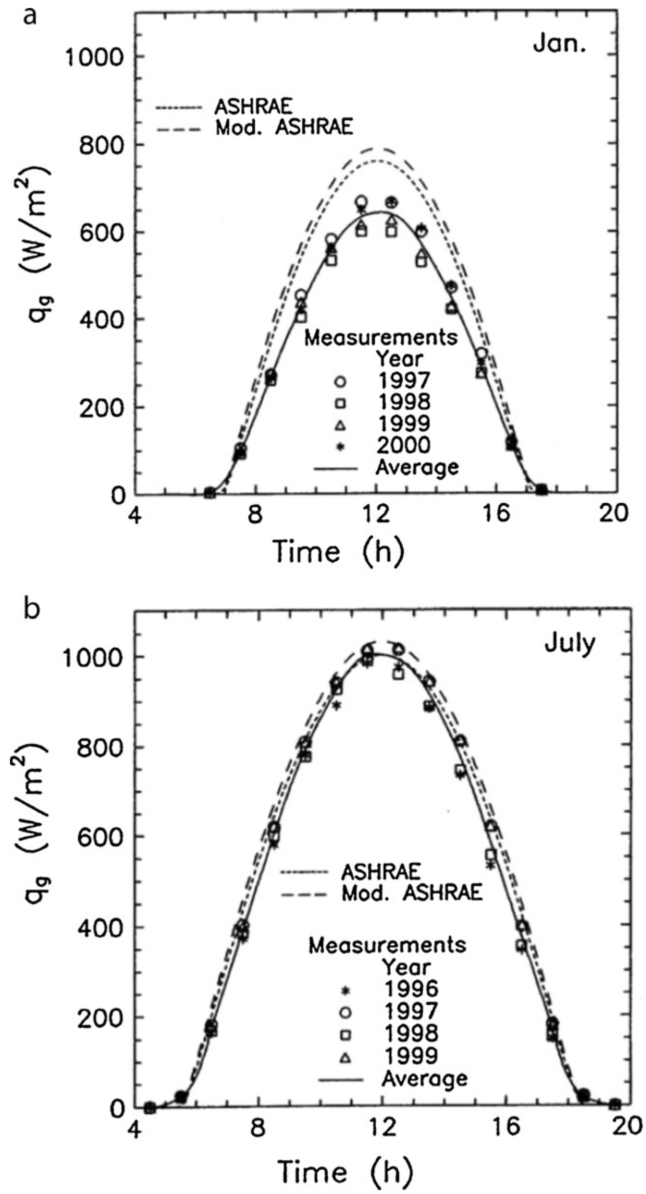


Fig. 6. Monthly-averaged hourly global-solar-radiation variations on horizontal surfaces in Riyadh; comparison between measurements and ASHRAE clear-sky-model calculations using original and modified sets of coefficients: (a) January and (b) July [63].

Al-Sanea et al. [63] used the ASHRAE clear-sky model for producing solar-radiation data on a horizontal surface in Riyadh on a quarter hourly basis for all days in each month of the year and compared with measurements for Riyadh, Saudi Arabia. They averaged both model results and measurements over the years 1996–2000 on an hourly basis for all days in each month of the year to get a monthly-averaged hourly variation of the solar flux. The ASHRAE model implemented utilized the standard values of the coefficients proposed in the original model, while calculations were made with a different set of coefficients proposed in the literature. The monthly-averaged hourly variation of the measured global (beam plus diffuse) solar radiation on horizontal surfaces in Riyadh for January and July is illustrated in Fig. 6(a) and (b), respectively, where the symbols signify different years and the solid line is the average over these years [63]. The results presented for January in Fig. 6(a) indicated that the ASHRAE model consistently over-predicted the measurements at all times. This was expected since the model did not account for local weather conditions such as the presence of clouds and dust. Also, it should be noted that there were discernible differences between the measurements for different years. This was mainly attributed to local cloud formations in this wintry month, which obviously varied from year-to-year. However, on a monthly averaged hourly basis, these variations had actually been reduced quite substantially. In contrast, the results presented for July in Fig. 6(b) showed that both the measurements and the ASHRAE model predictions differed only slightly. In fact, there was a reasonably close agreement between the results of the ASHRAE model and the mean values of the measurements. Based on the daily total solar-flux, a factor was also obtained for every month to adjust the calculated clear-sky flux in order to account for the effects of local dust and cloud conditions. When these factors were taken into account in the ASHRAE model calculations, the results agreed very well with the measured monthly-averaged hourly variation of the solar flux. It was also recommended that all future solar-energy applications, such as building energy analyses, employing the climatic conditions of Riyadh, be performed using the solar flux produced by the ASHRAE model corrected by the adjustment factors proposed in the present study.

5.3.2. *Solar PV systems*

As listed in Table 1 and highlighted by Sayigh [64], the PV power systems have been part of the Saudi electricity network since January 1985. Kettani [65] reported great interest in PV conversion in the Arab world and denoted the importance research in universities and applications in the field, while he give overview of all this activity and explained the reasons for this interest. He also specifically defined "economic attractiveness factors" such as "insolation factor" and "remoteness factor" that determined whether a PV application would be economical at a given geographical point.

In this regard, Sayigh [65] reported that under the auspices of a joint commission on economic cooperation, Saudi Arabia and United States signed a $100 million agreement in late 1977 for 5 years (the so-called SOLERAS), while he give the details of the PV power system considered. He also explained that one of the major objectives of this cooperation was to improve the quality of rural life in Saudi Arabia using solar systems for isolated communities, in agriculture and local industries. Sayigh concluded that the solar village experiment in Saudi Arabia was the biggest project of its kind in 1980, while he mentioned that availability of five different PV villages in the Arab World was meaningful.

Salim and Eugenio [66] presented a comprehensive report on the performance of a 350 kW concentrator solar PV power system by briefly summarizing the system design, fabrication and installation phases, and dealing in great detail with the performance, including the problems and failures experienced over a period of 7 years. They also reported that when installed in September 1981, it was the largest in the world at the time and was the only large concentrator PV power system in operation, while the system had performed remarkably well and had met or exceeded most of its design goals. Based on the long term performance of this system, large PV systems were indeed reliable sources of power with minimum operation and maintenance requirements. The system had been operated in several different modes, which included stand-alone and co-generation with diesel generators. It was connected to the utility grid and operated in the peak power tracking mode. It was expected that in the very near future, the system would have the additional capability of being directly coupled to a 350 kW electrolyzer to produce hydrogen.

Alawaji et al. [67] selected solar energy for supplying electric power to the equipment used in the desalination plant consisted of submersible pump, reverse osmosis unit, storage batteries, etc. due to the high insolation intensities in Saudi Arabia. They discussed about the various pieces of equipment in the PV systems along with their primary operation and performance.

Alajlan and Smiai [68] reported design and development of a PV plant for water pumping and desalination in remote area, which was the first of its kind in Saudi Arabia. The plant had two main PV separate systems. The first one was a PV water pumping system, which was characterized by storing the water in two storage tanks and without electric energy storage. The second one was a PV system for the operation of the reverse osmosis unit (water desalination), which was characterized by the storage of electric energy (batteries). The total installed PV capacities for pumping and desalination systems were 980 W_p and 10. 89 kW_p, respectively. The head of the submersible pump was 50 m from surface level, while the amount of water production from Reverse Osmosis Unit was about 600 L/h.

Al Harbi et al. [69] applied two methods of solar energy, namely PV (the direct conversion of sun light beam into electrical energy) and thermal method (the utilization of the sun's dissipated heat into useful applications to a hybrid one system, the so-called PV-thermal system). They assessed this system under the Saudi Arabian environmental conditions.

Hasnain and Alajlan [70,71] proposed a solar still plant with a daily distillate capacity of 5.8 m^3 to couple with the existing PV-RO plant in order to utilize most of the reject brine instead of throwing on the ground. They estimated the cost of product water as 0.50 US$/$m^3$, while they also concluded that the single effect solar stills for small scale plants was more viable to use in remote area, where the land value was negligible, while solar stills are easy to install and maintain and could be fabricated with locally available material.

Elhadidy and Shaahid [72] utilized hourly wind-speed and solar radiation measurements made at the solar radiation and meteorological monitoring station, Dhahran in Saudi Arabia to analyze and study the impact of key parameters such as PV array area, number of wind machines, and battery storage capacity on the operation of hybrid (wind + solar + diesel) energy conversion systems, while satisfying a specific annual load of 41,500 kWh. The monthly average daily values of solar radiation for Dhahran varied between 3.6 and 7.96 kWh/m^2. Based on a parametric study conducted, with two 10 kW wind machines together with three days of battery storage and PV deployment of 30 m^2, the diesel back-up system should provide about 23% of the load demand. However, with elimination of battery storage, about 48% of the load should be provided by diesel system.

Rehman et al. [73] presented a case study on the possibility of using PV technology for a campus site in Abha, Saudi Arabia and utilized the GSR data on horizontal surface to undertake an economic feasibility. The data utilized were retrieved including annual and seasonal variation of GSR on horizontal surface, temperature and relative humidity to understand the climatic conditions and availability of solar radiation for Abha city. The analysis covered three scenarios with daily average energy demands of (i) full load, (ii) 75% load and (iii) half load with annual peak load of 3.84, 3.06 and 2.27 kW, respectively. Each of these loads was further studied economically to investigate the effect of the battery storage for 1–5 days. It was concluded that the battery storage capacity cost played an essential role in the overall cost of PV system and hence the battery storage for smaller time period should be considered. For full load scenario, the cost of energy from the PV system was 29% cheaper compared to the diesel generating cost. For the 75 and 50% load systems, the cost was about 56 and 116% higher than the PV system, respectively. It was also recommended that larger PV systems should be preferred over the smaller ones.

The burning of depleting fossil fuels for power generation has detrimental impact on human life and climate. In this context, renewable solar energy sources are being increasingly exploited to meet the energy needs. Moreover, solar PV–diesel hybrid system technology promises lot of opportunities in remote areas which are far from utility grid and are driven by diesel generators. Integration of PV systems with the diesel plants is being disseminated worldwide to reduce diesel fuel consumption and to minimize atmospheric pollution. Saudi Arabia, which is endowed with high intensity of solar radiation is a prospective candidate for deployment of PV systems and also has a large number of remote scattered villages [3].

Shaahid and El-Amin [3] analyzed solar radiation data of Rafha, Saudi Arabia, for performing a techno-economic feasibility of hybrid PV–diesel–battery power systems to meet the load requirements of a typical remote village Rawdhat Bin Habbas (RBH) with annual electrical energy demand of 15,943 MWh. Rafha is located near RBH. NREL's Hybrid Optimization Model for Electric Renewable (HOMER) software was utilized in the assessment. It was reported that the location being blessed with considerable monthly average daily GSR intensity (3.04–7.3 kWh/m^2) was a prospective candidate for deployment of PV power systems. The simulation results indicated that for a hybrid system composed of 2.5 MW_p PV system together with 4.5 MW diesel system and a battery-storage of 60 min of autonomy (equivalent to 1 h of average load), the PV penetration was 27%. The cost of generating energy (COE) from the hybrid PV–diesel–battery system considered was obtained to be 0.170 US$/kWh with a diesel fuel price of 0.1$/L. Using this hybrid system, about 1005 tons/year of carbon emissions could be avoided entering into the local atmosphere. It was also recommended that the observations of this study could be employed as a benchmark in designing/sizing of hybrid PV–diesel–battery systems for other locations having similar climatic and load conditions.

Rehman et al. [22] utilized monthly average daily GSR and sunshine duration data to study the distribution of radiation and sunshine duration over Saudi Arabia. They performed an economical analysis of a 5 MW installed capacity PV based grid connected power plant for electricity generation using RetScreen software for energy production and economical assessment. The minimum and maximum GSR values were obtained to be 1.63 MWh/m^2 yr and 2.56 MWh/m^2 yr at Tabuk and Bisha, respectively, with an average value of 2.06 MWh/m^2 yr. The duration of sunshine varied between 7.4 and 9.4 h, with an overall mean of 8.89 h. The specific yield was found to vary from 211.5 to 319.0 kWh/m^2, with an average value of 260.83 kWh/m^2. The renewable energy produced each year from 5 MW_p installed capacity plant was ranged from 8196 to 12,360 MWh, while it was on average 10,077 MWh/yr. Based on the some economical indicators, such as internal rate of return, the simple payback period, the years to positive cash flows, the net present value, the annual life cycle savings, the profitability index and the cost of renewable energy production indicated that Bishah was the best site for PV based power plant development and Tabuk the worst. From the environmental point of view, it was found that on an average an approximate quantity of 8182 ton of greenhouse gases could be avoided entering into the local atmosphere each year from a 5 MW capacity PV plant in any part of Saudi Arabia. It was also recommended that more detailed techno-economical feasibility study should be conducted for Bishah site, while a pilot plant should be developed there and monitored to overcome the various aspects of technology transfer and adoption in Saudi Arabia. It could help in studying the engineering performance of such a power plant in the local environment.

Shaahid and Elhadidy [74] utilized the same software explained in Ref. [3] and performed a techno-economic feasibility of utilizing hybrid PV–diesel–battery power systems based on long-term solar radiation data of Dhahran (East-Coast, Saudi Arabia) to meet the load of a typical residential building (with annual electrical energy demand of 35,120 kWh). The monthly average daily solar global radiation varied between 3.61 and 7.96 kWh/m^2. The simulation results indicated that for a hybrid system composed of 4 kW_p PV system together with a 10 kW diesel system and a battery storage

of 3 h of autonomy (equivalent to 3 h of average load), the PV penetration was 22%. The COE of this hybrid system was obtained to be 0.179$/kWh with a diesel fuel price of 0.1$/L. It was concluded that the potential of solar energy could not be overlooked and a fraction of Saudi Arabia's energy demand could be harnessed from PV systems. It was also recommended that the findings obtained could be employed as a frame-of-reference in designing of hybrid PV–diesel–battery systems for other locations having similar climatic and load conditions.

Shaahid et al. [75] analyzed wind speed and solar radiation data of Rafha, KSA, and assessed the technical and economic potential of hybrid wind–PV–diesel power systems to meet the load requirements of a typical remote village Rawdhat Bin Habbas (RBH) with annual electrical energy demand of 15,943 MWh. Rafha is located near RBH. The monthly average daily GSR ranged from 3.04 to 7.3 kWh/m^2. The hybrid systems simulated consisted of different combinations of 600 kW wind machines, PV panels, supplemented by diesel generators. NREL's HOMER software was utilized to perform the techno-economic study. The simulation results indicated that for a hybrid system comprising of 1.2 MW wind farm capacity (two 600 kW units, 50 m hub-height) and 1.2 MW of PV capacity together with 4.5 MW diesel system (three 1.5 MW units), the renewable energy fraction with 0% annual capacity shortage was 24% (10% wind + 14% PV). The COE of this hybrid wind–PV–diesel system was found to be 0.118$/kWh with a diesel fuel price of 0.1$/L.

Rehman and Al-Hadhrami [76] also made an attempt to explore the possibility of utilizing power of the sun to reduce the dependence on fossil fuel for power generation to meet the energy requirement of a small village Rowdat Ben Habbas, located in the north eastern part of Saudi Arabia. They used the hourly solar radiation data measured at the site along with PV modules mounted on fixed foundations, four generators of different rated powers, diesel prices of 0.2–1.2 US$/L, different sizes of batteries and converters to find an optimal power system for the village. The existing diesel only system with four diesel generating units of 1500, 1000, 1750 and 250 kW with diesel price of 02$/L was found to be most economical power system with levelized cost of energy (COE) of 0.19$/kWh. The next best system with 21% solar PV (2000 kW$_p$) penetration; four diesel generators of 1250, 750, 2250 and 250 kW; battery bank (300); and a power converter of 3000 kW with a COE of 0.219$/kWh was economical at a diesel price of 0.2$/L. With the increase in the fuel price, the diesel only system was found to be less economical and at a fuel price of 0.60$/L and above, the diesel only system became un-economical compared to that of the hybrid power system. It was recommended that a demonstration hybrid power system with 20% solar PV penetration should be developed, while practical aspects of the development, operation, maintenance and thereof improvement should studied.

5.3.3. *Solar stills*

There is an urgent need for clean, pure drinking water in many countries. Water sources are often brackish and/or contain harmful bacteria and therefore cannot be used for drinking purposes. There are also many coastal locations where sea water is abundant, but potable water is not available. Pure water is also needed in some industries, hospitals and schools. Solar distillation is one of the many processes that can be used for water purification. Solar radiation can be the source of heat energy where brackish or sea water is evaporated and is then condensed as pure water [77]. In this regard, El-Sebaii [77] presented transient mathematical models for a single slope-single basin solar still with and without phase change material (PCM) under the basin liner of the still. Analytical expressions for temperatures of the still elements and the PCM have been obtained. They derived the energy balance equations for the various elements of the still as well as for the PCM during charging and discharging modes, while they solved them analytically. Numerical calculations were also undertaken for typical summer and winter days for Jeddah in Saudi Arabia to study the effect of the mass of stearic acid on the daily productivity and efficiency of the still. Comparisons between the results obtained for the still with and without the PCM indicated that using 3.3 cm of stearic acid under the basin liner, 9.005 (kg/m^2 day) of fresh water could be obtained on a summer day with a daily efficiency of 85.3%. The PCM was more effective for lower masses of basin water on winter season.

El-Sebaii et al. [78] also investigated an active single basin solar still integrated with a sensible storage material by computer simulation using the climatic conditions of Jeddah, Saudi Arabia. Sand was used as a storage material due to its availability. In the analysis, the flowing water temperature was assumed to vary with time and space coordinates. Analytical expressions were obtained for various temperatures of the still elements as well as for the temperature of sand. Effects of mass flow rate and thickness of the flowing water for different masses of the storage material on the daylight, overnight and daily productivity and efficiency of the still were studied. The following main conclusions were drawn: (i) The daily productivity decreased with the increase in the mass of sand. (ii) The daily productivity and efficiency decreased with the increase in the thermal conductivity of the basin linear material. (iii) On a summer day, a daily productivity value of 4.005 kg/m^2 with a daily efficiency of 37.8% was obtained using 10 kg of sand compared to that of 2.852 kg/m^2 with a daily efficiency of 27% when the still was used without storage. The annual average of daily productivity of the still with storage was calculated to be 23.8% higher than that when it was used without storage, and (iv) The present still with a sensible storage material could be operated, under weather conditions similar to Jeddah, as a source of the hot water required for some domestic and low temperature industrial applications all year round.

5.3.4. *Solar-powered irrigation*

Solar-powered agricultural irrigation seems to be an attractive application of renewable energy, while for practical uses it should be feasible in terms of both technical and economical aspects. In this context, Kelley et al. [79] developed a method for determining the technical and economic feasibility of PV powered irrigation systems, applicable to any geographic location and crop type and applied to several example cases. They expressed the feasibility as a function of location, which covered climate data, aquifer depth and cost, including local political policies such as carbon taxes. A discounted cash flow analysis was also utilized to compare the lifecycle costs of PV-, diesel engine- and electrical grid-powered irrigation systems. Technical feasibility was determined from the maximum power required for irrigation, which depended on crop type and geographic location. Economic feasibility was based on comparing lifecycle costs of PV powered irrigation systems to diesel- and grid-based irrigation systems. Carbon taxes and financial incentives for installing alternative energy systems were taken into account in the method, although they were not applied to the examples. The results obtained from the technical feasibility analysis agreed with those from the previous studies. It was concluded that there was no technological barrier to implementation of PV powered irrigation and the limiting factor was land availability; as long as there could be physical space for the panels, there would no reason why they could not be used to power an irrigation system.

Said [80] reported the economic competitiveness of PV-powered irrigation when compared to conventional diesel powered pumps in Saudi Arabia. He also conducted a cost comparative study and presented a breakdown cost of a solar PV module of US$2.5/W at a peak load.

5.3.5. Solar energy-related greenhouses

Radhwan et al. [81] experimentally investigated the thermal performance of an agricultural greenhouse (GH) with a built-in solar distillation system, which was constructed at the King Abdul Aziz University, the city of Jeddah, Saudi Arabia. They also highlighted some measures towards improving the productivity of the GH solar distillation. A set of solar basins with saline water was placed on the greenhouse roof to reduce the GH cooling load and to produce the required fresh irrigating water by solar distillation. The ventilation air entered the GH through an evaporative cooler for cooling in the summer (and hot days), and was partially recirculated for heating in the winter (and cold days). The system transient performance (temperatures and humidity inside the plant growth zone and water productivity) was presented for the summer of July 2004. Under the summer climatic conditions of the city of Jeddah, the results indicated that the GH inside temperatures could be 8–10 °C and 3–6 °C at the GH inlet and outlet below the ambient temperature, respectively. The GH inside relative humidity ranged from 20% to 35% above the ambient conditions, within the comfort zone of plant growth.

Al-Helal and Alhamdan [82] investigated the effect of outdoor exposure of a greenhouse polyethylene cover to the arid environment over a period of 13 months. Measurements of global solar radiation (GSR), photosynthetically active radiation (PAR), air temperature and relative humidity were made inside and outside two single-polyethylene-covered model structures. It was found that the reduced solar radiation resulted in minimizing inside air temperatures, while GSR and PAR transmittances depended on the season where they were highest during the winter months. At certain exposure periods, a noticeable decrease of the relative losses was also observed due to rainfall cleaning of dirt and dust deposited on the polyethylene film. It was recommended that cleaning the greenhouse cover should be made especially in cold months and the rate of dust accumulation density should be defined in relation to its effect on solar transmittance through covers with different greenhouse configurations. For a future work, investigating the amount and type of solar radiation in commercial greenhouses at the plant canopy and its availability to the plant canopy beneath was also recommended.

The protected cultivation in greenhouses has became the favored way to develop the agriculture sector due to the harsh climate, scarce and poor-quality of water resources in the Arabian Peninsula. For managing crop production and improving operation and production efficiencies, it is very essential to predict and control environmental conditions in greenhouse. Simulation models have been mostly used to predict the greenhouse environment because they provide a quick, less expensive and more flexible and repeatable way compared with predictions based on experiments [83]. In this regard, Abdel-Ghany and Al-Helal [83] presented the general relations for estimating the amounts of solar energy absorbed by the greenhouse components and lost to outside the greenhouse. These relations included the interrelations as well as the multiple reflections of solar radiation between these components. Thus, the greenhouse system was treated as a solar collector having an absorber plate (i.e., the greenhouse soil) and a cover system consisting of three semi-transparent parallel layers (i.e., the greenhouse cover, the humid air, and the plants). The analysis was made through superposition theory and ray tracing technique, while the relations considered were applied to an experimental plastic-covered greenhouse with a floor area of 34 m^2. The greenhouse, located in Riyadh, Saudi Arabia, was planted with tomatoes with a leaf area index (LAI) of 3.0 and was cooled by a wet pad and fan system. Fig. 7(a) and (b) illustrates the distribution of the incident solar energy among the greenhouse components during the day and the daily integral of each energy component, respectively [83]. Here, S_G is the solar energy incident on the greenhouse, S_c, S_p, S_s and S_w indicate the solar energy absorbed by the greenhouse cover, the plants, the soil and the humid inside air, respectively, while S_L is the solar energy lost to outside the greenhouse. Because the plant density was high (LAI = 3), about 37% of the incident solar energy was absorbed by the plants. However, the floor soil absorbed 15%; the covering material absorbed 13.5% and the water vapor absorbed less than 1%. The rest (about 33.5%) was lost to outside the greenhouse by: (i) Reflection on the outer surface of the cover. (ii) Backward reflections on the plants and soil surfaces then escaped to outside the greenhouse. (iii) Transmittance of the incident radiation through both sides of the greenhouse cladding when the solar elevation was low in the morning and afternoon. It was also concluded that the relations given were capable of precisely predicting the distribution of the global incident solar radiation among the components of a greenhouse with a maximum error of 2% in the results of each relation at a LAI of 1.5 and this error significantly would be decreased to less than 0.7% if the LAI in the greenhouse could be increased to 5.

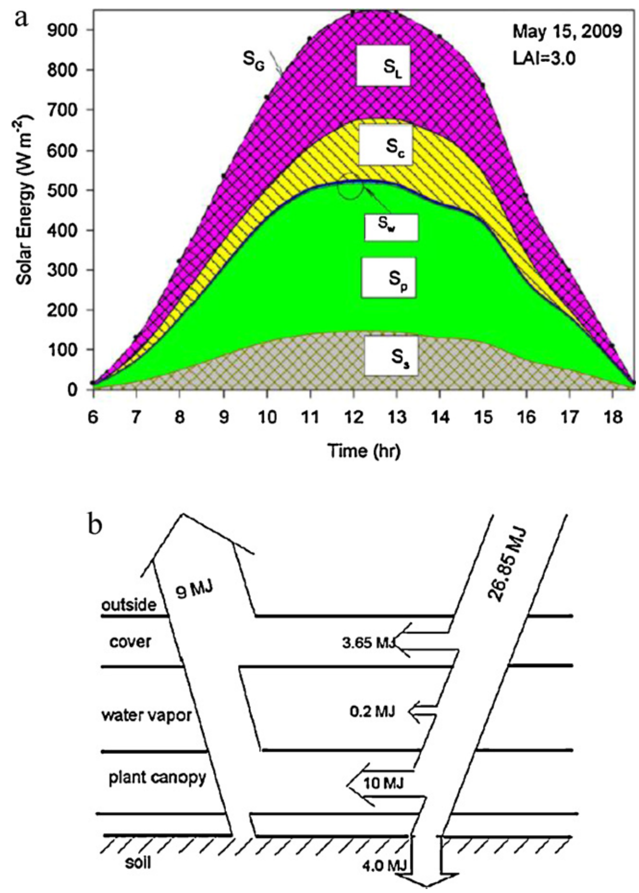


Fig. 7. (a) Distribution of the incident solar energy among the greenhouse components and (b) daily integrals of the distributed solar energy on a sunny summer day (May 15, 2009) of Riyadh climate [83].

5.3.6. Solar hydrogen

Since 1986 Kingdom of Saudi Arabia and Germany have been cooperating in the research, development and demonstration of solar hydrogen production and its utilization through the HYSOLAR project. A solar hydrogen production demonstration plant, which could have been considered as the world's first 350 kW solar-powered hydrogen-generation plant at the time of its inception, had been designed, installed and operated in the Kingdom of Saudi Arabia at the KACST research site (solar village) about 50 km North West of Riyadh. The plant was started up on 19 August 1993 and

utilized the DC electricity being produced by 350 kW of electricity produced by PV cells [84,85].

Zahed et al. [86] highlighted that in spite of the present vast reserves of oil and natural gas of the country, the proposition of converting the abundant non-depletable solar energy (2500 kWh_{th}/m^2 on a nominal area of 1.3 million km^2) into hydrogen via electrolysis of water was considered as necessary, viable and challenging. They reported that at that time when this study was conducted, non-energetic consumption of hydrogen (estimated at about 8000 million m^3/year) was derived primarily from fossil fuels. In this context, they aimed at harnessing solar energy for large scale production of hydrogen to be used as a main non-fossil fuel to gradually substitute the oil and gas, in all possible areas of utilization, while discussing a comprehensive perspective of present and future utilization of hydrogen in the country.

Grasse et al. [87] explained the German-Saudi Arabian HYSOLAR program along with its background, origin, purpose and structure. They also presented the program goals, the results achieved until that time and the future perspectives, while a list of some HYSOLAR-related publications was also included in the Appendix of their study.

Abdel-Aal [88] proposed a less conventional approach to store solar energy, which implied the decomposition of water to produce hydrogen using energy from the sun (in the form of heat and/or electricity). The conversion of solar radiation first into usable energy was investigated via three possibilities, namely (i) direct energy conversion using PV cells from water electrolysis, (ii) concentration to thermal energy using a central receiver system for the electrolysis, and (iii) the thermochemical decomposition of water and helio-hydro-electric power generation for water electrolysis. Thermodynamic features of the water-splitting processes including thermochemical cycles were presented first. Experimental findings using small-scale PV electrolysis units were then reported from the production of hydrogen. Finally, the criteria for selecting regions and locations for hydrogen production on a massive scale in some parts of the Arab World were established.

Abdel-Aal and Hussein [89] investigated the electrolysis of saline water for the production of hydrogen. They reported that the main difficulties anticipated were the evolution of chlorine gas as the anodic product and the gradual build-up of insoluble precipitates on the cathode surface. They made a comparison between the established processes of electrolyzing alkaline water and brine, on the one hand, vs saline water electrolysis on the other. A number of parameters were also examined, including salinity, voltage, current density and quantity of electricity, while their effects on hydrogen production were also reported using a modified simple Hoffman electrolysis cell.

Steeb et al. [13] explained in more detail the HYSOLAR, which was started in 1986. They also briefly reviewed the most important results and addressed the open questions and problems. An outlook into the programme's second phase contents, where more emphasis was laid on hydrogen utilization technologies, was also included. In this context, it was highlighted that the first phase of HYSOLAR, which ended in 1991, focused mainly on investigation, test and improvement of hydrogen production technologies. The participants from research institutions and universities in both countries have reported on their work in more than 90 scientific publications.

Daous et al. [90] described a complete solar hydrogen research plant, which was part of the HYSOLAR program, by outlining the safety aspects of its design and operation. This plat was put into operation in November 1989. It was reported that since then until the time when this study was conducted, over 1 MWh was utilized to produce hydrogen without any major problem. Only two minor incidents reported in their study occurred during this period. Some recommendations regarding the safety aspects were presented in the light of the experience gained during the operation of the plant. It was concluded that these were also applicable for larger plants based on similar technology.

Al-Garni [91] reported that catalytic combustion of hydrogen was considered to be one of the safest, cleanest and most efficient forms of utilizing hydrogen for heating purposes. He also comprehensively presented experimental setup, investigation procedures and study results conducted at KACST, in order to find a general purpose catalytic combustion module. The main conclusions drawn were as follows: (i) Catalytic combustion with ceramic-based porous substrates proved to be probably the most suitable option for stable heating purposes with hydrogen, exhibiting good temperature uniformity and satisfactorily resisted surrounding air fluctuations, and (ii) With hydrogen, in the absence of products causing catalyst poisoning, degradation of the catalytic combustion activity was shown to be relatively unlikely for long operation cycles.

Abdel-Aal and Al-Naafa [92] surveyed the Arab world for the availability of new and renewable energy sources including solar energy and presented two case studies for Egypt and Saudi Arabia. A classification was also made based on the level of development and on the energy balance of each Arab country. The target was to utilize these energy sources for hydrogen production and hence for desert development claiming more arable land. It was pointed out that hydrogen would be harnessed along the following avenues: (i) to provide energy for land development, (ii) to provide energy for pumping and irrigation, (iii) to produce fresh water, and (iv) to produce fertilizers based on ammonia as a starting raw material. Some concluding remarks drawn were as follows: (i) The Arab countries have the potential to produce a total of more than 2×10^{12} m^3 of solar hydrogen annually based on utilizing 1% of the available area, 10% efficiency for solar conversion, and 30% efficiency for hydrogen production, and (ii) The energy supplied by solar hydrogen could lead to an increase in the area of arable land thus compensating for the loss in agriculture land in Egypt and land desertification in Saudi Arabia.

Abaoud and Steeb [93] gave a very condensed overview on the manifold activities in the German-Saudi bilateral RD&D program HYSOLAR. Concentrating on Phase II of the program – which ended in 1995 – recent results in the fields of solar hydrogen production (the 350 kW solar hydrogen production demonstration plant and the 10 kW test and research facility), hydrogen utilization (catalytic combustion of hydrogen, fuel cell technology and hydrogen engines), fundamental research (instationary combustion phenomena in a hydrogen fueled engine and photoelectrochemical energy conversion), system studies and concentrating PVs were shortly reviewed. It was concluded that competent research teams have developed valuable technical and experimental equipment as well as demonstration plants which have been built, while HYSOLAR has stimulated numerous other activities on the national and international scale.

Almogren and Veziroglu [85] developed a model for the solar-hydrogen energy system for Saudi Arabia using a formulation of continuous dynamic interaction between the population, energy, economic parameters and the resources. The variables considered were population, energy demand, energy production, hydrogen production, energy prices, gross national product, environmental damage and quality of life.

Two hydrogen introduction scenarios were considered as given by the following hydrogen introduction doubling times [85]:

$$\theta_h = 2 + 0.15(n - 1), \quad \text{for Case 1} \tag{35}$$

$$\theta_h = 4 + 0.15(n - 1), \quad \text{for Case 2} \tag{36}$$

Fig. 8 illustrates the projection of energy demand of Saudi Arabia with the solar-hydrogen production [85]. If the solar hydrogen is

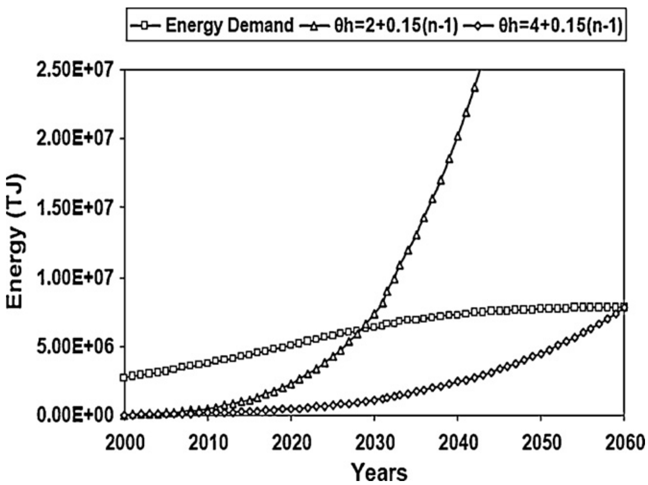


Fig. 8. Projections for Saudi Arabia energy demand and solar hydrogen energy production [85].

produced at this rate and the energy demand continues at this rate or less, Saudi Arabia would be able to provide its energy needs as solar-hydrogen energy in 2028 and 2060 in the Cases 1 and 2 based on Eqs. (35) and (36), respectively. In addition, it would have more hydrogen for export in later years after getting its energy need.

The results also indicated that the oil resources of Saudi Arabia would not be enough to meet the domestic and export markets starting in three to four decades. It could do so by solar production of hydrogen and then utilizing hydrogen as an energy carrier, as well as exporting it to other countries. This would provide Saudi Arabia with a clean and permanent energy system, and would enable it to maintain and improve its overall GNP, as well as improving its quality of life.

Zaidi et al. [94] explained research activities and/ongoing projects undertaken at KFUPM for the development of fuel cell systems. They reported that research at KFUPM was focused on two different aspects, fuel for fuel cells (reformat feed) and Proton Exchange Membrane (PEM) fuel cell system. Their research group at KFUPM has been actively involved in fuel cell research since 1980s. They concluded that the research in the fuel cell area would provide futuristic benefits to Saudi Arabia as this technology has been commercialized in many advanced countries and the market penetration of this technology would depend on the rate of technological advancements.

5.3.7. Solar water desalination

With increasing the water demand and emphasis on desalination technology due to shortage of underground resources in the Kingdom, the government of Saudi Arabia established the Saline Water Conversion Corporation (SWCC) in 1974. Since then, the SWCC has grown and become the authority to look after all matters related to seawater desalination [95]. Within the scope of SOLERAS-Saudi Arabian-United States Program for cooperation in the field of solar energy program, a solar-powered seawater desalination pilot plant was completed in 1984 at the coastal city of Yanbu. One of the goals of the program was to incorporate solar Technologies into those industrial applications that require thermal or electric energy. The plant used an indirect-contact heat transfer freeze process to produce 200 m^3 of potable water each day. The pilot plant also used 18 point-focus collectors (each with a surface area of 80 m^2) with dual axis tracking for solar energy collection. The total cost of this program was around US$35.3 million [5,96].

The Kingdom of Saudi Arabia has begun building the first solar-powered water desalination plant, the first step in a three-part program to introduce solar energy into the Kingdom. In this regard, the KACST, Saudi Arabia's national research and development organization launched a program. The main objective of this program is to help stabilize future power and water supplies inside Saudi Arabia through the creation of solar-powered desalination facilities [17].

In February 2008, IBM and KACST signed a multi-year collaborative research agreement, under which scientists from IBM and KACST work side by side at IBM Research labs in New York and California as well as at the KACST/IBM Nanotechnology Centre of Excellence in Riyadh, Saudi Arabia. IBMs multi-faceted research with KACST also includes exploring new ways to recycle polyethylene terephthalate (PET) plastics, commonly used for food and beverage containers [17].

The research collaboration between IBM (NYSE:IBM) and KACST is expected to aim at creating a water desalination plant powered by solar electricity, which could significantly reduce water and energy costs [16,17]. KACST and IBM have developed a research center to determine how best to harness and repurpose this solar energy and prepared to implement this state-of-the-art technology [15].

Prince Dr. Turki bin Saud bin Mohammad, KACST Vice President for Research Institutes denoted, "The solar energy program will reduce the cost of producing desalinated water and of generating power for use in the Kingdom, an oil-dependent nation, which has launched a national energy efficiency program." [16].

The expected production capacity of the new, energy efficient desalination plant is 30,000 m^3/day. This plant will be built in the city of Al Khafji to serve 100,000 people and is planned to be powered with the ultra-high concentrator PV technology that is being jointly developed by IBM and KACST; this technology is capable of operating a Concentrating PV (CVP) system at a concentration greater than 1500 suns. Inside the plant, the desalination process will hinge on another IBM-KACST jointly developed technology, a nanomembrane that filters out salts as well as potentially harmful toxins in water while using less energy than other forms of water purification. According to KACST scientists, the two most commonly used methods for seawater desalination are thermal technology and reverse osmosis. The cost of both methods varies between 2.5 and 5.5 Saudi Riyals/m^3. The cost of desalinating seawater at these plants is also expected to significantly reduce by combining solar power with the new nanomembrane [17].

One of the most efficient means of desalination is reverse osmosis. There are, however, obstacles to unlocking this reserve (principally bio-fouling, degradation by chlorine and low flux challenges). The KACST/IBM joint research focuses on improving polymeric membranes through nanoscale modification of polymer properties to make desalination much more efficient and much less costly. The collaborative research between KACST and IBM has led to innovative technologies in the areas of solar power and of water desalination. It is also expected that using new technologies energy-efficient systems can be created and implemented across Saudi Arabia and around the world [17].

As for as research studies conduced on solar desalination are concerned, Khoshaim [97] pointed out that the need to develop an industrial solar sea water desalination system for industrial, urban and rural application was of great interest to the SOLERAS Program. He introduced a pilot plant constructed in Yanbu, Saudi Arabia for testing and demonstrating the world's first and largest solar sea water desalination pilot plant at that time. This plant utilized the indirect freezing technology for the desalination system with 18 powerful point focus solar collectors. The aim was to provide energy to the system to produce 200 m^3/day of fresh potable water. Based on the preliminary results reported, the usefulness of those two new technological applications met 75% of the baseline design values, while an extensive research and testing program was set to provide the necessary data and operational history before deciding on further use of this technology on a commercial scale.

Al-Mutaz and Al-Ahmed [98] reported that solar desalination was considered the best alternative to provide fresh water in remote arid areas, while the selection of the appropriate solar desalination process was a unique problem ever done by processes comparison. In this context, they assessed possible solar desalination processes, for which the Arabian Gulf region was utilized as a reference. They also made a comparison between solar desalination and fossil fuel powered desalination plants for justifying the recommendation of the selected solar desalination process.

Zahed and Bashir [99] reported performance assessment valuation studies of Syltherm-800 (a proprietary heat transfer fluid) and Partherm-290 (a proprietary heat storage salt). The data were obtained from a solar powered freeze desalination pilot plant with a capacity of 200 m^3, located in Yanbu, Saudi Arabia over a 1-year operation period. It was concluded that in spite of some operational problems, the thermal stability of these heat transfer media was observed to be good, which ensured their prolonged use in solar power-generation technology.

5.3.8. Solar energy education

Husnain et al. [100] reported that scientists have established a bright future for solar energy utilization through their RD&D activities, but they paid less attention to solar energy education, necessary for effective dissemination of solar energy technologies. In this regard, they discussed about prospects and proposals on the development of proper education programs for every stage of education and the initiation of solar energy awareness solar energy awareness programs for the public.

Husnain et al. [101] also pointed out that the growing consumption of limited reserves of fossil fuels and their impact to the environment have raised global interest in harnessing solar energy while proper knowledge of solar energy is lacking in many levels of society. In this regard, they gave an overview of the current status of solar education program available around the globe and highlighted the importance of the energy information network for solar education program. A survey on the availability of solar energy education program around the world was conducted by the ERI-KACST. The main points to be drawn from the survey were as follows: (i) Only three universities of industrialized countries were conducting Master Degree Courses on solar energy/renewable, while no similar course was available in developing countries. Very few topics on solar energy/renewable (as elective course) were, however, available in institutes for undergraduate and postgraduate programs in developing countries, and (ii) The organizations based in industrialized countries were only putting their efforts to run training courses/seminars and some of those organizations were involved in the design of teaching resource materials, especially for school children. While organizations in developing countries were arranging seminars, conferences for technical personnel not targeting the young generation and non-technical personnel. It was recommended to cover solar energy subjects in the current curriculum at every level of education, especially in developing countries. It was concluded that Degree Courses (taught/research) on solar energy were required to be arranged for the creation of appropriate technical manpower in the field of solar for sustainable development, while a well organized solar energy information database/network was required to establish energy.

Since then, various academical programs on solar energy have been designed in Saudi Arabia, while different programs for enhancing public awareness about utilization of technologies based on renewable energies have also been conducted. As one of the recent activities in this regard, 5th Renewable Energy Workshop was held at KFUPM on 24 April 2010 under the title of Solar Energy Technology: Present & Future [102,103]. Main objectives were to (i) import knowledge from experts in the field of solar energy to the community, (ii) promote the environmental benefits of utilizing solar energy, (iii) educate the technical needs and the research requirements related to solar technology, (iv) to address the challenges and issues related to implementing the solar energy technology, (v) to explore future prospects in employing the solar energy technology developing know how of the current technologies in the area and future developments, and (vi) provide a platform within which participants can convey their thoughts about solar energy technology and educate themselves about its scenario in the near future [104]. In the scope of the workshop, Dr. Sayigh described general renewable energy topics and historical development of some solar energy-related studies in Saudi Arabia. Dr. Kazmerski began with a video of a U.S. Vanguard satellite going into orbit in the late 1950s, saying that this was the first solar powered satellite ever launched into orbit, as also denoted in another activity [105]. In this context, various current PV technologies with a focus on thin films including, copper indium gallium selenide (CIGS), cadmium telluride (CdTe), organic solar cells, and dye sensitized solar cells were briefly explained [106]. Solar hot water applications were explained and discussed in detail [107], while public lectures were also delivered within the scope of solar energy awareness program for the public [101,102].

5.4. Studies on solar energy utilization, development and applications

It was reported that RD&D activities have played a vital role in transferring technology to Saudi Arabia [6]. Development, utilization and application of solar energy in Saudi Arabia is briefly described below [5,6,84,108–113].

In this regard, a study on research into solar energy utilization in Saudi Arabia conducted by Sabbagh et al. [108] consisted of two parts. In the first part, they conducted a survey on general solar data for Saudi Arabia by including total solar radiation, the average sun duration, ambient temperatures and by comparing total radiation among some of the Middle Eastern capitals. The second part covered the design and performance of water heaters and distillers along with their application for domestic utilization purposes. Their aim was also to establish a solar energy laboratory, fully equipped for the measurement of all the solar data needed and to start working on a new project on solar air conditioning and PV conversion processes. They concluded that it was feasible to locally build an economical solar water heater with a daily hot water capacity of 50 L at an average of 70 °C and a water distiller with a daily average yield of 5 L, costing about $160.

Sayigh [109] took into consideration solar distillation, passive cooling, greenhouse technology, combined solar and geothermal systems, and solar economics in Saudi Arabia. He included the existence of three climatic regions, namely extremely arid, semiarid, and arid, while he presented an equation used to predict the solar intensity. It was reported that solar distillation was considered the most important solar application in Saudi Arabia, and research on single-slope solar stills and a multistage solar still was also mentioned. The water required for agriculture could be reduced using passive cooling and adobe greenhouses. It was concluded that in Saudi Arabia, solar water heating was cheaper than conventional methods while other solar applications were a little more expensive compared to existing means.

Huraib et al. [84] described the lessons learned from the major RD&D activities at ERI and KACST in the field of solar energy. They studied PV, solar thermal dishes, solar water heating, solar water pumping and desalination, solar hydrogen production and utilization for solar energy applications. Recommendations and guidelines for future solar energy research development, demonstration and dissemination in Saudi Arabia were also presented.

Al-Athel reported that [110] the first ever demonstration of solar cell usage was in 1954 by American Telephone & Telegraph (AT&T)

Company in Murray Hill, New Jersey (Bellis). However, Saudi Arabia was not far behind. The first PV energy was installed by the French at an airport in Medina in 1960. Since then, Saudi Arabia has invested many resources towards the development of solar energy in the Kingdom.

Rehman and Halawani [111] reviewed the available literature related to the development and utilization of solar energy in Saudi Arabia in 1998. They highlighted that Saudi Arabia undertook many projects related to the development of renewable sources of energy between 1978 and 1998.

Elani and Bagazi [112] discussed the potential of silicon development for PVs in conjunction with the availability of raw material and PV demand in Saudi Arabia. They also reported that spectral and chemical analyses of the local raw materials in the Riyadh region indicated that the average silicon oxide content in the white rock/sand had the highest ratio 99.5% compared to those obtained from red sand 86.7% and limestone 13.5%, while the white rock/sand was suitable for further development and particularly for use in PV manufacturing. It was concluded that silicon raw material for PV production should be considered for further investigation towards solar cells manufacturing in Saudi Arabia based on the studies conducted by KACST.

Alawaji [113] reported that recognizing sun as the main natural source of energy, with which Saudi Arabia is blessed in abundant measure, it is believed that solar energy is a valuable renewable source of energy, which should be fully utilized for the benefit of the country.

Alawaji's study [114] was based on a more detailed paper in Ref. [5]. He reported that the experience gained in the field of renewable energy R&D between 1980 and 2000 had been very valuable and the international joint programs had assisted in the establishment of a series of independent RD&D projects on solar energy by the ERI, and several other users throughout the country.

Said et al. [115] addressed the current status and the future potentials of renewable energy applications such as wind energy, solar energy and hybrid system, in Saudi Arabia. They presented some concluding remarks as follows: (i) A wealth of experience has been gained in the assessment, instrumentation, calibration, data collection, monitoring and analysis of solar energy projects. (ii) Low and medium solar thermal energy applications in the Kingdom of Saudi Arabia are technically and economically feasible and should be encouraged and supported by the government. (iii) More feasibility studies have to be conducted in the field of hybrid systems, and (iv) In developing countries, efforts should be directed to finding applications of those renewable systems that have already been developed in industrialized nations.

Rehman [116] pointed out that Saudi Arabia observes the longest sunshine hours and highest solar radiation intensity in the world and needs to be tapped for small and big applications. According to BP Solar Company in Riyadh, Saudi Arabia, the total PV installed capacity reached 3895 kW by the end of year 2008. Fig. 9 indicates a variation of the annual addition and cumulative PV installed capacities between 2002 and 2008 in Saudi Arabia [116]. Of the record, in Saudi Arabia, PV panels have been utilized for various applications since 1981. Some of these applications included a 350 kW installed capacity electricity generation plant for a remote village in Riyadh (Solar Village), a 350 kW PV system for hydrogen production (Solar Village), another 6 kW PV system for grid connected supply (Solar Village), 4 kW_p PV system for agriculture usage (Muzahmia), 10.63 kW_p PV system for sea water desalination (Sadus village, approximately 70 km from Riyadh), 57.60 kW_p PV lighting system for tunnels in southern region of Saudi Arabia, etc. Alawaji [5] reported that the cumulative PV installed capacity in Saudi Arabia totaled to 4 MW_p up to year 2000. Rehman [116] also denoted that at present, none of these applications are in use, while the other major applications of PV systems in Saudi Arabia cover the cathodic protection in oil and water pipe lines and the communication towers.

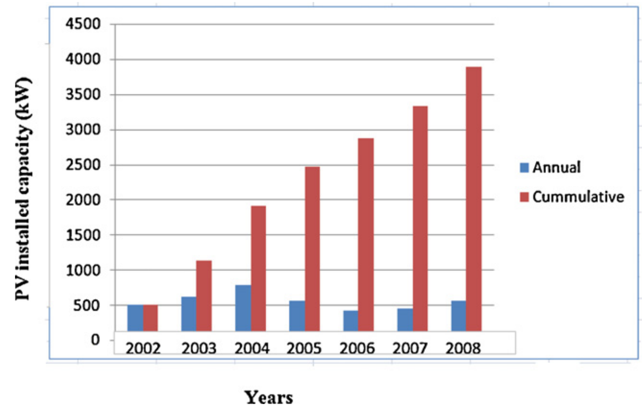


Fig. 9. A variation of the annual addition and cumulative PV installed capacities between 2002 and 2008 in Saudi Arabia.
Adapted from Ref. [116].

6. Future directions of solar energy studies: some recent advances

Some future aspects of solar energy in Saudi Arabia are briefly summarized below in the light of the recent developments and advances in the field of solar energy. These include solar desalination, solar hydrogen production, solar cooling and PVs, while parabolic-trough solar collectors and their applications have been comprehensively reviewed in Ref. [117].

6.1. Solar desalination

Water and energy are two of the most essential topics on the international environment and development agenda. The social and economic health of the modern world is significantly dependent on sustainable supply of both energy and water. Energy is a critical parameter for economic and of vital importance in social and industrial development, as it is also quality water. Numerous low-density population areas lack not only fresh water availability, but in most of the cases electrical grid connection or any other energy source as well, except for renewable energy sources, mostly referring to solar radiation. For these regions desalination is a moderate solution for their needs [118].

Table 4 indicates the relationship between various energy inputs and criteria for desalination technologies, while the recommended renewable energy–desalination combinations are also given elsewhere [119].

Renewable energy-driven desalination systems fall into two main categories: thermal processes and electromechanical processes. The share of the solar energy in renewable energy-driven desalination processes is 70%, with solar PV at 43% and solar thermal at 27%. As regards the energy source, a desalination plant powered by renewable energy is likely to be a stand-alone system at a location which has no electricity grid. Stand-alone systems are often hybrid systems, combining more than one type of renewable energy sources, for instance, wind and solar energy or including a diesel generator. In order to ensure continuous or semi-continuous operation independent of weather conditions, stand-alone systems usually include a storage device. Table 5 lists an overview of recommended combinations depending on several input parameters, while it should be noticed that additional combinations are also possible [118]. Solar desalination can either be direct; utilizing solar energy to produce distillate directly in the solar collector,

Table 4
Assessment of renewable energy technologies [119].

Criterion	Solar thermal energy	Photovoltaic	Wind energy	Geothermal energy
Suitability for powering desalination plants	Well suited for desalination plants requiring thermal power (3)	Well suited for desalination plants requiring electrical power (3)	Well suited for desalination plants requiring electrical power (3)	Well suited for desalination plants requiring thermal power (3)
Site requirements and resources availability	Typically good match with Need for desalination (3)	Typically good match with need for desalination (3)	Resources is location-dependent (2)	Resources is limited to certain location (1)
Continuity of power output	Output is intermittent (energy storage required) (1)	Output is intermittent (energy storage required) (1)	Output is intermittent (energy storage required) (1)	Continuous power output (3)
Predictability of power output	Output is relatively unpredictable (2)	Output is relatively unpredictable (2)	Output is very unpredictable/fluctuates (1)	Output is predictable (3)

3, excellent compliance with criterion; 2, good compliance with criterion; 1, poor compliance with criterion.

or indirect; combining conventional desalination techniques, such as multistage flash desalination (MSF), vapor compression (VC), reverse osmosis (RO), membrane distillation (MD) and electrodialysis (ED), with solar collectors for heat generation. Direct solar desalination compared with the indirect technologies requires large land areas and has a relatively low productivity. It is, however, competitive to the indirect desalination plants in small-scale production due to its relatively low cost and simplicity [120].

To exploit solar energy substantially, means are required for it to power medium- to large-capacity desalination plants. All desalination technologies can be coupled with solar energy, but solar thermal is most appropriate for thermal processes (MSF or MED), while PVs can supply electric energy for processes such as VC or RO, as seen in Table 6 [118,121,122].

Seawater desalination can resolve the fresh water problem in numerous countries in both the Near East and Mediterranean region. Despite its reliability, the relatively high energy consumption still remains to be resolved. Because areas largely exposed to water scarcity are characterized by high levels of solar radiation, consideration should be given to the opportunity of using solar energy, coupled to desalination processes. This is particularly true in isolated and far remote areas, having no access to the electric grid [121].

Saudi Arabia is a prime location to harness solar energy because of its year-round sunshine. Water desalination is critical to providing clean drinking water around the world. Today, Saudi Arabia produces 18% of the world's desalinated water, currently being the largest producer of desalinated water in the world. Because over 97% of the world's water is in the oceans, turning salt water into fresh water cost effectively and energy efficiently offers tremendous potential for addressing the growing worldwide demand for clean water. By building water desalination plants that run on solar energy, the Kingdom can reduce operational costs and in turn, reduce consumer costs [15,16].

Existing and emerging desalination technologies, recent advances and possible combinations of renewable energy sources to drive them and associated desalination costs have been reviewed and discussed in Refs. [123–128]. In this regard, among the possible combinations of desalination and renewable energy technologies, solar and wind energy sources have been greatly exploited and found to be more promising in terms of economic and technological feasibility [127]. It was also reported that solar-powered desalination technologies are suitable and may be the only technically and economically competitive alternative for small desalination capacities up to 10 m^3/day to provide drinking water in remote areas where access to fuel, electricity, and technical expertise is not available. Focusing areas of solar thermal desalination in today's and future studies cover three aspects, which are also directly related to economic performance improvements of the systems considered: (i) enhancing solar-energy collection, (ii) improving the technology of desalination techniques, and (iii) better matching the solar [126].

6.2. Solar hydrogen production

Hydrogen is one of the most promising future energy carriers, and one of the most promising ideas is the solar-hydrogen energy system. The advantage of such a system is that it is clean with no harm for the environment, and is renewable [85]. Hydrogen is acclaimed to be an energy carrier of the future and can not only be used as a direct form of energy as a fuel for internal

Table 5
Recommended renewable energy-desalination combinations [118].

Feed water quality	Product water	Renewable energy resource available	System size			Suitable combination
			Small	Medium	Large	
Brackish water	Distillate	Solar	■		■	Solar distillation
	Potable	Solar	■		■	PV-RO
	Potable	Solar	■		■	PV-ED
	Potable	Wind	■	■	■	Wind-RO
	Potable	Wind	■	■	■	Wind-ED
Seawater	Distillate	Solar	■			Solar distillation
	Distillate	Solar		■	■	Solar thermal-MED
	Distillate	Solar			■	Solar thermal-MED
	Potable	Solar	■			PV-RO
	Potable	Solar	■			PV-ED
	Potable	Wind	■	■		Wind-RO
	Potable	Wind	■	■		Wind-ED
	Potable	Wind		■	■	Wind-MVC
	Potable	Geothermal		■	■	Geothermal-MED
	Potable	Geothermal			■	Geothermal-MED

Note: PV, photovoltaic; RO, reverse osmosis; ED, electrodialysis; MED, multi-effect desalination; VC, vapor compression; MSF, multi-stage flash.

Table 6
Recommended options for coupling solar energy and desalination along with thermal and economic characteristic values for some desalination technologies.

Desalination process	Possible type of solar energy supply			Characteristic						
				Capacity (m^3/day)		Energy consumption (kWh/m^3)			Cost	
	PV	Solar thermal	Solar thermal (electric)	Typical average	Maximum average	Thermal	Electric	Equivalent electric	Plant [\$/(m^3/day)]	Production (\$/m^3)
MSF		√	√	25,000	50,000	80	4	15	1300	1.1
MED		√	√	10,000	20,000	60	2	7	1200	0.8
RO	√		√	6000	10,000	–	5	5	1000	0.7
VC	√		√	3000	5000	–	7	7	1000	0.7

Adapted from [118,121,122].

combustion engines but also can be used as a media to store energy (e.g., metal hydrates). Currently, it is mainly produced by fossil fuels, which release greenhouse gases and other climate-changing emissions. Thermochemical cycles, such as hybrid-sulphur cycle, metal oxide based cycle and electrolysis of water are the most promising processes for environmentally benign hydrogen production for the future. It can be produced using solar energy in different ways namely; using solar electricity and solar thermal energy. The idea of using solar energy is to protect environment from the unwanted greenhouse gas emissions [129].

Hydrogen production using solar energy can be classified mainly into four types, which include (i) PV, (ii) solar thermal energy, (iii) photo electrolysis and (iv) biophotolysis. The thermal energy from solar energy can be utilized into two ways, namely low temperature and high temperature application also called concentrated solar energy. PV, photo electrolysis and bio photolysis are considered as low temperature application whereas solar thermolysis, solar thermochemical cycles, solar gasification, solar reforming and solar cracking are high temperature applications of concentrated solar thermal energy. Concentrating solar energy can also be utilized to produce steam and then using the power of steam electricity can be produced. The produced electricity can be utilized to produce hydrogen via electrolysis. In this communication the above method is considered in solar thermal applications only. Four major ways in which solar energy can be utilized to produce hydrogen are illustrated in Fig. 10 [129]. The water electrolysis using PVs is the most mature method to produce hydrogen. Photoelectrolysis is still at an early stage of development and material cost and practical issues have yet to be solved. The photobiological processes are also still at a very early stage of development and thus far only low conversion efficiencies have been obtained. High temperature processes need further materials development, which focuses on high temperature membranes and heat exchangers for solar thermal processes. The world's solar hydrogen utilization systems, therefore, consist mainly of PV hydrogen systems for transportation and stationary applications. Ecofriendly hydrogen production through solar energy is very essential to help conserve the environment as it does not emit any greenhouse gases to it during operation. At present it is a challenging task for researchers and scientists as the exergy efficiency of the PV array is low and hence, the overall exergy efficiency of a solar hydrogen system [129].

6.3. Solar cooling

Energy consumption in the residential sector is one of the main parts of the total energy consumption in most countries around the world. Worldwide energy utilization by heating, ventilating, and air-conditioning (HVAC) equipment in buildings forms a significant part of total energy consumption, depending on the countries and their sectoral energy utilization patterns. In Saudi Arabia, the electrical energy consumption in the residential sector is almost the same as the sum of the other sectors. In this context, the share of the residential sector in the total consumption in 2006 was 50%, followed by the industrial sector with 23%, the governmental sector, which included streets, hospitals, mosques and charity associations with 16%, the commercial sector with 9% and the agricultural sector with 2% [130]. Because the residential sector is the most energy consumer in Saudi Arabia, in this sector, three quarter of total electricity is consumed by building HVAC systems [131]. Due to the importance of the solar cooling in Saudi Arabia, development of solar cooling laboratories in the universities was conducted by the ERI, KACST between 1981 and 1987 [5]. Saudi Arabia participated in projects that SOLERAS researched and developed in the U.S., as well as in the Kingdom to reduce the cost and improve the efficiency of air cooling systems [132,133]. Effective utilization of solar cooling in Saudi Arabia, however, has not yet made reasonable progress.

Although several solar refrigeration technologies are considered mature, until today, the total cooling capacity of the solar air conditioning systems in Europe is only 6 MW [134]. Although each technology has its own positive and negative aspects, high initial cost is a common problem. A variety of options are available to convert solar energy into refrigeration effect.

Solar thermal systems, in addition to the typical advantages of renewable resources (environmentally-friendly, naturally replenished, distributed), are very suitable for air-conditioning and refrigeration demands due to solar radiation availability and cooling requirements, which usually coincide seasonally and geographically. Solar air-conditioning and refrigeration facilities can also be easily combined with space heating and hot-water applications and with solar passive techniques, increasing the yearly solar fraction of buildings [117]. In spite of the tremendous research effort made in theoretical analysis and experimental projects since the 1970s, and the enormous interest related to solar air-conditioning and refrigeration systems, their commercial implementation is still at a very early stage. The main reason for this is high costs associated with these systems and the clear market supremacy of conventional compression chillers. Other obstacles to their large-scale application are the shortage of small heat pump equipment and the lack of practical experience and acquaintance among architects, builders and planners with their design, control and operation [117,135].

Kim and Infante Ferreira [134] have comprehensively reviewed the main options and ranks according to their reported performance and the required investments per kW cooling. Fig. 11 illustrates a comparison of various solar refrigeration technologies in terms of performance and initial cost, although differing in technical maturity and commercial status. The three last columns indicate the specific cost of PV solar panels, the specific cost of thermal solar collectors plus specific engine costs and the specific chiller cost, respectively. Solar electric systems are assumed to be equipped with 10%-efficient solar PV panels with a unit price at €5/W_p. These solar panels convert a solar radiation of 1000 W/m^2

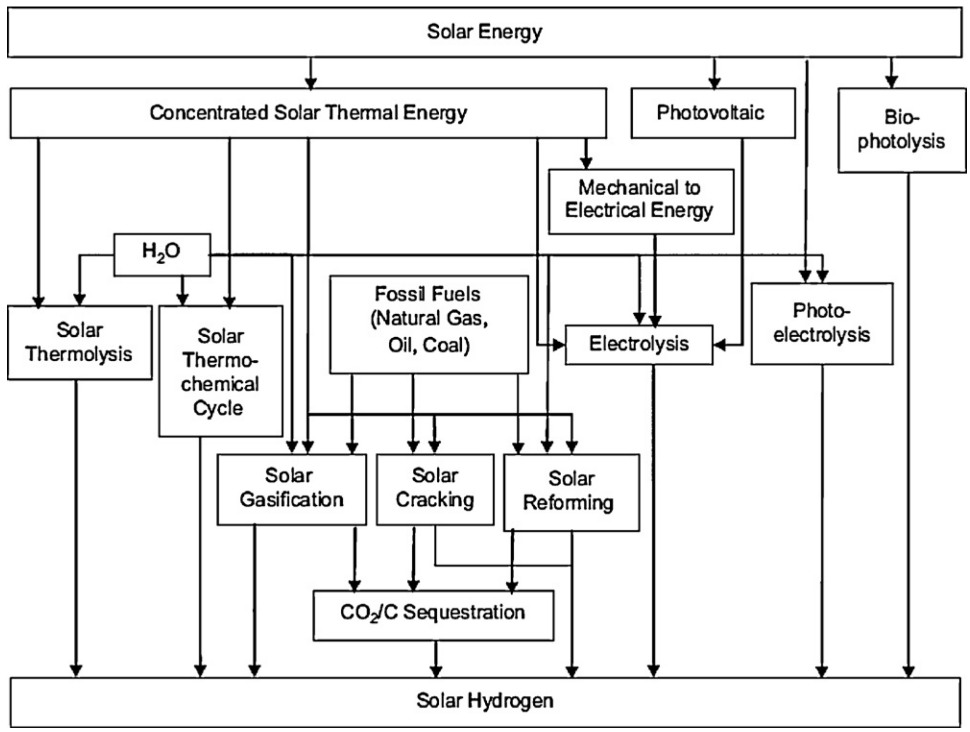


Fig. 10. Solar hydrogen production methods [129].

into 100 W of electricity and the various electric chillers transform this electric energy into cooling power according to their specified coefficient of performances (COPs).

Solar thermal with a single-effect absorption system appears to be the best option closely followed by the solar thermal with a single-effect adsorption system and by the solar thermal with a double-effect absorption system options at the same price level. Solar thermo-mechanical or solar PV options are significantly more expensive. Here the vapor compression system and magnetic systems are the most attractive options, followed by the thermo-acoustic and Stirling systems. Desiccant cooling (DEC) and ejector systems will be more expensive than the first three systems. The exact position of these systems, however, is difficult to identify because they systems require specific equipment.

Regarding the direction of future R&D in solar refrigeration, it would better be focused on low-temperature sorption systems. The reasons for this are as follows: The cost of a solar collector system tends to increase with working temperature more rapidly than COP of a sorption machine does. High temperature-driven chillers would not be compatible with the existing solar heating

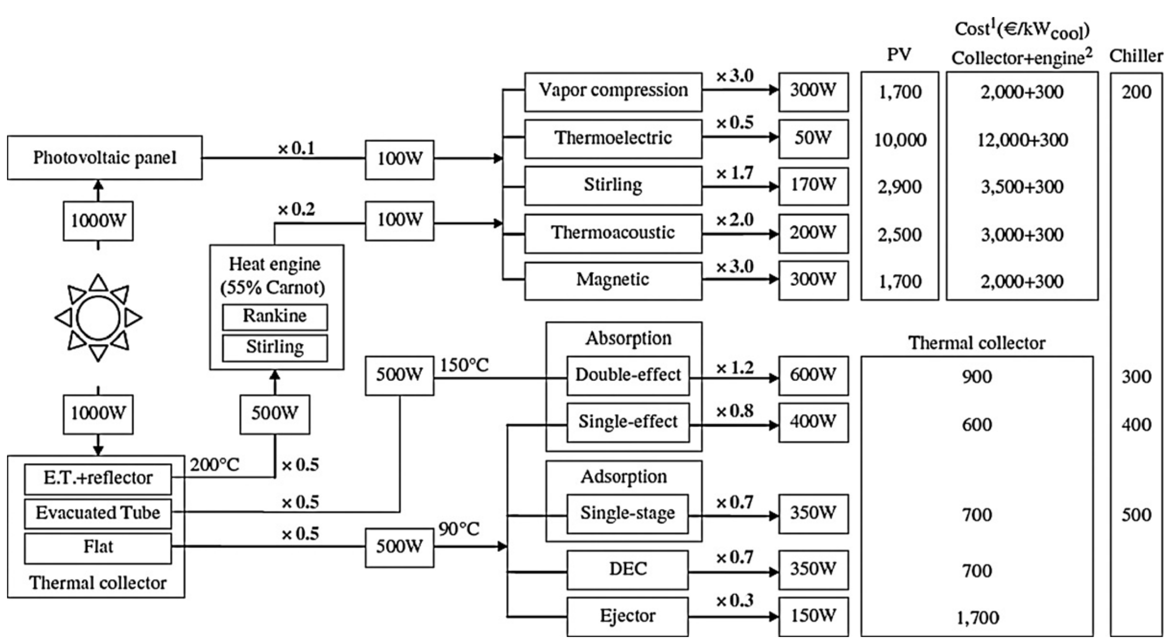


Fig. 11. Performance and cost of various solar refrigeration systems [134]. [1]Based on retail prices without installation, rounded off below €100. [2]Assumed to be 150% of a vapor compression chiller cost. DEC, desiccant cooling.

systems which were originally designed to produce domestic hot water. Another important subject in the future R&D is the development of air-cooled machines. Currently, there is only one air-cooled machine for solar cooling in the market. Its performance, however, seems to become unsatisfactory for ambient air temperatures above 35 °C. A wet cooling tower is unfavorable in most of the small applications where regular maintenance work is impossible or in the arid regions where water is scarce [134].

It is also reported that the COP is higher for a LiBr–H_2O double-effect than for a single-effect absorption chiller, but it requires thermal energy at temperatures of 140–160 °C [116,135]. In this temperature range, the performance of conventional collectors is not good enough. Due to higher efficiency values of parabolic-trough collectors (PTCs) at these temperatures, the combination of these two systems is of great interest [116,136]. Connection of NH_3–H_2O absorption chillers to a solar system requires solar collectors able to work efficiently at temperatures above 95 °C [116,137], such as the PTCs or high-efficiency stationary collectors. Air-conditioning and refrigeration facilities driven by a PTC solar field are still infrequent, while several test facilities using this technology have, however, appeared in the literature during the last 50 years.

6.4. Photovoltaics

PV technology is proven and easy to use solar energy for generating electricity. It is being globally used to supply power to remote communities, utility peak load shaving, cathodic protection in pipelines, remotely located oil fields and gas oil separation plants, telecommunication towers, highway telephones and billboard, off-grid cottage/s, resorts in desert areas, water pumping for community and irrigation, municipal park lighting, exterior home lighting and many other utilization [22].

Parida et al. [138] have comprehensively reviewed major solar PV technologies, which included PV power generation, hybrid PV generation, various light absorbing materials, performance and reliability of PV system, sizing, distribution and control. The light absorbing materials covered silicon, CdTe and cadmium sulphide (CdS), organic and polymer cells, hybrid PV cell, thin film technology and some other solar cells. The different applications of solar PV system, such as building integrated system, desalination plant, space, solar home systems and pumps. Problems associated with PV technology, were also presented and discussed.

Kazmerski [104,106] comprehensively explained and discussed PV technologies, worldwide PV production values between 1990 and 2007, best research-cell efficiencies between 1975 and 2010, technology investment pathways, such as performance comparisons, thin film PV technologies, etc., concentrator PVs, efficiency values for ideal future generation solar cells ranging 40.3% (Shockley & Queisser limit) to 95% (ideal converter; T_s = 6000 K, T_a = 300 K, isotropic illumination), being 85.4% for both solar thermal and thermo PV, and nanotechnology (Si Quantum dot films).

Towards the future directions of PV, the following was highlighted by some investigators [139–141], as reviewed by Parida et al. [138]. It was reported that PV is one of the fastest growing industries worldwide and in order to maintain this growth rate need for new developments with respect to material use and consumption, device design, reliability and production technologies as well as new concepts to increase the overall efficiency arises [138]. Feltrin and Freundlich analyzed several PV technologies, ranging from silicon to thin films, multi-junction and solar concentrator systems for terawatt level deployment of the existing solar cells, and for each technology, identified improvements and innovations needed for further scale-up [140]. Solar PV electricity was described as the solution of future energy challenges, while the modular approach adopted to meet the year 2025 energy demand of six major cities in India indicated that the suggested solar hydrogen based energy network had the capability of providing the energy requirements [141].

7. Some barriers, scenarios and constraints

For several decades, Saudi Arabia has undergone rapid population growth and economic and industrial development, which have increased the energy demand and requiring more power generation to meet it. With the continued growing number of residential and industrial customer connections to the power grid, the surge in electricity demand is projected to continue its growth to reach double its current size by the year 2023. To prepare for future increase in power demand, numerous power projects have been launched throughout Saudi Arabia for achieving the projected expansion in the power industry. Existing power plants have been constantly upgraded and expanded, while numerous new power facilities, including electricity generation and desalination cogeneration plants, have been constructed. Private companies have also significantly contributed to the expansion in the power industry by constructing two major plant types, namely Independent Power Producer, and Independent Water and Power Producer [142].

Due to the export potential of its oil reserves and its decision to allocate gas as a feedstock to its petrochemical industries rather than as a fuel for electricity generation, Saudi Arabia has economic incentives to develop renewable energy to meet domestic electricity demand [143]. After the pilot schemes to develop solar energy in the 1980s, Saudi Arabia is taking a much more active approach to solar power development [4].

Saudi Arabia appears to have great natural potential for solar power generation. Public officials have made statements about how Saudi Arabia would like to become a large-scale exporter of solar electricity within the next 30–50 years by covering the desert with solar power plants in the same way that the Desertec project would generate electricity for export to Europe. This is a long-term aspiration, currently rendered unfeasible by technological limitations. To date, there have been few projects in the solar sector in Saudi Arabia, other than small off-grid uses of PV technology. However, Saudi Arabia is now attempting to develop its own renewable energy technology hub [143].

Taleb [144] identified the real barriers hindering the utilization of geothermal resources in Saudi Arabia. In this context, the interview questions were prepared in order to explore the barriers to the lack of utilization of geothermal energy in Saudi Arabia, as well as to identify some enablers that could be used to tackle the identified obstacles. The barriers were divided mainly two subgroups, namely technical and non-technical (political, economic, social and educational) barriers. The main economic-related barrier was the availability of a cheap source of energy (i.e., fossil fuels), which is a heavily-subsidized energy source in this oil-rich country. This is also valid for solar energy development, while political support is a vital element for a successful renewables and solar energy could incorporate social benefits, such as employment and investments opportunities as well as financial profits. It is also reported [4] that the enhanced utilization of solar power should, logically, contribute to price stability in the solar energy markets, as the sun's power is unlimited and quite stable in the cloudless desert. However, most experts estimate that it will take at least another decade to bring the cost to the projected values.

Al-Saleh [145] presented and developed a set of renewable energy scenarios for Saudi Arabia using the Delphi technique. It was concluded that many of the oil-rich Middle Eastern nations have benefited enormously from the recent surge in oil prices. This ample income has provided Saudi Arabia, as a major oil-producer, with options that would have been unthinkable a few years ago.

Among the challenges facing such oil-dependent economies, however, is how such an apparent wealth can be put to the best use on the path to sustainable development. Demonstrably, almost all energy scenarios for attaining sustainability around the world take for granted a sizeable increase in the share of primary energy from renewable sources. With the recent energy and environmental concerns, there is an apparent global enthusiasm for renewable energy options. Saudi Arabia, despite being a key oil producer should not be seen as an exception in this regard. It is believed that 'now' is the appropriate time to invest in developing capabilities in the field of renewable energy in order to secure the country's future for a sustainable economy and to address its rapidly-growing energy needs. The drive towards renewable energy in Saudi Arabia should not regarded as being a luxury but rather a must, as a sign of good governance, concern for the environment and prudence in oil-production policy.

Implementing the sustainable investments in the gulf region can also support the renewal EU–GCC partnership as well as play an important role in initiating a cleaner and environmentally sound energy market. Using the sustainable energy technologies that have already proven to be competitive, GCC companies can make a profit today, while creating a path for the future technological advantages. As GCC business becomes experienced with installation and maintenance on a large scale, new markets for these technologies will open up, creating even more competitive opportunities. In addition, the increased impact of the climate change on the energy sector, due to these states' recent accession to the Kyoto protocol, brings out these investments as key means for establishing conditions of security, stability and sustainability. However, significant efforts need to be made for renewable energy technologies to be fully commercialized and competitive. Nowadays, it is clearly illustrated that there exist a significant space for improvements of renewable energy exploitation in the region, as reported in more detail elsewhere [146].

8. Conclusions

Saudi Arabia has great natural potential for solar power generation and economic incentives to develop renewable energy to meet domestic electricity demand. Specifically, the rapid development in solar energy technology has made it the most promising alternative to conventional energy systems in recent years. After the pilot schemes to develop solar energy in the 1980s, Saudi Arabia has taken a much more active approach to solar power development. In this study, we comprehensively reviewed present status and future directions of solar energy studies in terms of various aspects, such as solar desalination, solar hydrogen production, solar cooling and PVs. We also presented some barriers, scenarios and constraints associated with the solar energy studies implemented. In this regard, we listed some concluding remarks as follows:

(a) Saudi Arabia has a considerably high level of solar energy potential that can be a part of the total energy network in the country.
(b) Saudi Arabia has enormous potential for exploiting solar energy. Saudi Arabia can, therefore, be a leading producer and exporter of solar energy in the form of electricity, if a major breakthrough is achieved in the field of solar-energy conversion [5].
(c) Saudi Arabia was among the first countries to invest in renewable energy research through major joint international cooperation programs, where the Saudi government provided one-half of the funds needed, and the other half was provided by developed countries, such as United States and Germany. The most infamous program, established 31 years ago, was called SOLERAS a joint venture between Saudi Arabia and the United States in mutual cooperation [110].
(d) Some renewable energy investments seem to be more available and effective solutions in the region, because of specified conditions and requirements in remote (e.g., mountains in Saudi Arabia) and isolated areas (e.g., islands in Bahrain). For example, there exist a very high potential for the application of solar energy in Global System for Mobile Communications (GSM), road lighting, cooling and desalination. These systems can enhance the quality of life in these regions, through the delivery of modern social services. The efforts should be focused on the building of scientific and political consensus, via setting up of a number of communication channels on different policymaking and policy-drafting levels, such as websites, publications and workshops for stake holders. Close contacts and effective interaction need to be achieved between centers of research and development and local market in order to bring the new developed products to practice [146].
(e) Renewable and energy-efficient technologies can meet a substantial portion of the energy needs of Saudi Arabia. Renewable energy, particularly solar energy, is an abundant resource in the country, and holds huge economic promise. In the process of shifting new investment to these energy forms, numerous public benefits will be created, including the enhanced environmental quality, increased energy security, and local economic development benefits [7].
(f) Even though the Arab States of the Gulf region is a leading oil and natural gas producer, they should be interested in taking an active part in the development of technologies for exploiting and utilizing renewable energy. The use and development of renewable energy Technologies (in particular solar energy) could make a significant contribution to improving environmental protection and to guaranteeing continuing oil supplies in conditions of stability and security in the Gulf region [146].
(g) Water has been the first priority in the Science, Technology and Innovation Plan of Saudi Arabia, as overseen by KACST. Saudi Arabia is currently the largest producer of the desalinated water in the world. In this regard, investments in new ways of making access to fresh water more affordable are expected to significantly increase in the country [17].
(h) The use of renewable energies for desalination appears nowadays as a reasonable and technically mature option towards the emerging and stressing energy and water problems. Although intensive research world-wide has been undertaken, the actual penetration of RES-powered desalination installations is too low.
(i) A primary challenge with desalination remains large energy use and related environmental impacts. These and other socially negative impacts can in part be offset using renewable energy resources for desalination. For example, nearly 3 kg of CO_2 generation for each m^3 of water produced (at an energy consumption rate of 5 kWh/m^3 with the best technology currently used on large-scale) can be avoided if conventional fuels are replaced with renewable energy [121,122].
(j) Abaoud and Veziroglu [20] developed a model for Saudi Arabian solar-hydrogen energy system. They indicated that (i) adopting the solar-hydrogen energy system would extend the availability of oil resources, reduce pollution, and establish a permanent energy system for Saudi Arabia, and (ii) Saudi Arabia could also become an exporter of hydrogen forever.
(k) More feasibility studies have to be conducted in the field of hybrid systems. In this regard, the market penetration of these systems should be promoted and facilitated by demonstrating the cost-effective and environmentally friendly solution to be provided.
(l) Due to the importance of the solar cooling in Saudi Arabia, the number of projects for development or demonstration of solar refrigeration technologies and solar refrigeration should

be increased. In this regard, a variety of solar refrigeration technologies have been developed and many of them are available in the market at much cheaper prices than ever [134].

(m) The utilization of PV modules for grid connected and as well as hybrid systems have been studied by the researchers at universities and the institutes in Saudi Arabia, with 3895 kW of PV installed capacity by the end of year 2008 [116].

(n) A switch towards more efficient use of fossil fuels and an increased share of renewable energies would have several benefits not only for Saudi Arabia, but also for other GCC countries: if the domestic use of fossil fuels were reduced, more oil and natural gas could be exported [12].

(o) Solar radiation data are a fundamental input to solar energy applications, such as PV, solar–thermal systems and passive solar design, they should be reliable and readily available for simulation, design, optimization and performance assessment of various solar technologies at any particular location. In this regard, For estimating the solar radiation in various cities of Saudi Arabia, different correlations have been developed by many investigators, as reviewed in this study.

(p) Exergy is a way to sustainable development. In this regard, exergy analysis is a very useful tool, which can be successfully used in the performance evaluation of solar energy systems as well as all energy-related systems. In this regard, the number of studies conducted on exergetic analysis and assessment of solar energy systems is relatively low in Saudi Arabia. It is recommended that this useful tool be utilized for performance assessment purposes of solar energy-related systems, as done for geothermal energy resources in Saudi Arabia elsewhere [147].

(q) Achieving sustainable development is a target that is now widely seen as important to worldwide public opinion. In this context, the utilization of renewable energy resources such as solar, geothermal, and wind energy appears to be one of the most efficient and effective ways of achieving this target [148].

(r) The results are expected to be beneficial to the researchers, government administration, and engineers working in the area of solar energy systems as well as in establishing energy polices.

References

[1] Chen HH, Kang H, Lee AHI. Strategic selection of suitable projects for hybrid solar-wind power generation systems. Renewable and Sustainable Energy Reviews 2010;14:413–21.

[2] Holm D, Arch D. Renewable energy future for the developing world. Freiburg, Germany: International Solar Energy Society (ISES). White Paper; 2005.

[3] Shaahid SM, El-Amin I. Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia—a way forward for sustainable development. Renewable and Sustainable Energy Reviews 2009;13:625–33.

[4] Dargin J. Saudi Arabia, UAE promote energy from sun and wind. Oil & Gas Journal 2009;107(12):18–22.

[5] Alawaji SH. Evaluation of solar energy research and its applications in Saudi Arabia—20 years of experience. Renewable and Sustainable Energy Reviews 2001;5:59–77.

[6] Alawaji SH, Hasnain SM. Role of solar energy research in transferring of technology to Saudi Arabia. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 1999;21(10):923–34.

[7] Alnatheer O. The potential contribution of renewable energy to electricity supply in Saudi Arabia. Energy Policy 2005;33:2298–312.

[8] Wilhelm E, Fowler M. A technical and economic review of solar hydrogen production technologies. Bulletin of Science Technology Society 2006;26(1):278–87.

[9] Balachandra P, Nathan HSK, Reddy BS. Commercialization of sustainable energy technologies. Renewable Energy 2010;35:1842–51.

[10] Sakr I. Solar energy applications in the Arab world. In: Daghestani FA, Gocht WR, Mulki HF, editors. Proceedings of the International Seminar on appropriate technology in the fields of solar and wind energy applications. Amman, Jordan: Royal Scientific Society; 1987.

[11] Lowenstein MZ, Smith IC. The Joint Saudi Arabian-United States Solar Energy Program. In: American Institute of Aeronautics and Astronautics, Terrestrial Energy Systems Conference. 4–6 June 1979. p. 6 p. http://adsabs.harvard.edu/abs/1979tesy.confS..L, accessed 13 May 2010.

[12] Reiche D. Energy policies of Gulf Cooperation Council (GCC) countries-possibilities and limitations of ecological modernization in rentier states. Energy Policy 2010;38(5):2395–403.

[13] Steeb H, Seeger W, Aba Oud H. Hysolar: an overview on the German-Saudi Arabian programme on solar hydrogen. International Journal of Hydrogen Energy 1994;19(8):683–6.

[14] NASA Remote Sensing Validation Data: Saudi Arabia. http://rredc.nrel.gov/solar/new_data/Saudi_Arabia/, accessed December 26, 2010.

[15] Anonymous. Saudis planning to invest in solar energy. Asia News; 3 April 2008.

[16] Anonymous. Royal Embassy of Saudi Arabia; Saudi Arabia Launches Solar Energy Program. Energy Business Journal 26 February 2010:332.

[17] Anonymous. IBM, KACST unveil research initiative to desalinate seawater using solar power. Nanotechnology Weekly; 19 April 2010 p. 34.

[18] KACST, King Abdulaziz City for Science and Technology. Home. http://www.kacst.edu.sa/en/about/stnp/Pages/default.aspx, accessed 25 November 2010.

[19] KACST, King Abdulaziz City for Science and Technology. Information about KACST. http://www.kacst.edu.sa/en/about/Pages/default.aspx, accessed 25 November 2010.

[20] Abaoud HA, Veziroglu TN. Energy kingdom. Energy Conversion and Management 2002;43:855–61.

[21] KACST, King Abdulaziz City for Science and Technology. Strategic Decision for the Country. http://www.kacst.edu.sa/en/about/media/news/Pages/news98.aspx, accessed 25 November 2010.

[22] Rehman S, Bader MA, Al-Moallem SA. Cost of solar energy generated using PV panels. Renewable and Sustainable Energy Reviews 2007;11:1843–57.

[23] Ulgen K, Hepbasli A. Diffuse solar radiation estimation models: a review with an illustrative example. Energy Conversion and Management 2009;50:149–56.

[24] El-Sebaii AA, Al-Hazmi FS, Al-Ghamdi AA, Yaghmour SJ. Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia. Applied Energy 2010;87:568–76.

[25] Shaahid SM, Elhadidy MA. Wind and solar energy at Dhahran, Saudi Arabia. Renewable Energy 1994;1(4):441–5.

[26] Rehman S, Ghori SG. Spatial estimation of global solar radiation using geostatistics. Renewable Energy 2000;21:583–605.

[27] Sabbagh JA, Sayigh AAM, Salam EMA. Correlation of solar radiation and sunshine duration in Riyadh. Spakistan Journal of Scientific and Industrial Research 1973;16.(16).

[28] Anane-Fenin K. Estimating solar radiation in Ghaha. International Atomic Energy Agency (IAEA) and United Nations Educational Scientific and Cultural Organization (UNESCO). International Centre for Theoretical Physics; April 1986 21 p.

[29] Sabbagh JA, Sayigh AAM, El-Salam EMA. Estimation of the total solar radiation from meteorological data. Solar Energy 1977;19:307–11.

[30] Bakhsh H, Srinivasan R, Bahel V. Correlation between hourly diffuse and global radiation for Dhahran, Saudi Arabia. Solar & Wind Technology 1985;2(1):59–61.

[31] Bahel V, Srinivasan R, Bakhsh H. Solar radiation for Dhahran, Saudi Arabia. Energy 1986;11(10):985–9.

[32] Abdelrahman MA, Elhadidy MA. Comparison of calculated and measured values of total radiation on tilted surfaces in Dhahran, Saudi Arabia. Solar Energy 1986;37(3):239–43.

[33] Al Mahdi N, Al Baharna NS, Zaki FF. Assessment of solar radiation models for the Gulf Arabian countries. Renewable Energy 1992;2(1):65–71.

[34] Zuhairy AA, Sayigh AAM. Simulation and modeling of solar radiation in Saudi Arabia. Renewable Energy 1995;6(2):107–18.

[35] Rehman S, Halawani TO. Global solar radiation estimation. Renewable Energy 1997;12(4):369–85.

[36] Rehman S. Solar radiation over Saudi Arabia and comparisons with empirical models. Energy 1998;23(12):1077–82.

[37] Al-Ayed MS, Al-Dhafiri AM, Bin Mahfoodh M. Global, direct and diffuse solar irradiance in Riyadh, Saudi Arabia. Renewable Energy 1998;14(1–4):249–54.

[38] Rehman S. Empirical model development and comparison with existing correlations. Applied Energy 1999;64(1–4):369–78.

[39] Khogali AM, Ramadan RI, Ali ZEH, Fattah YA. Global and diffuse solar irradiance in Yemen (YAR). Solar Energy 1983;31(1):55–62.

[40] Aksakal A, Rehman S. Global solar radiation in Northeastern Saudi Arabia. Renewable Energy 2009;17:461–72.

[41] Benghanem M, Joraid AA. A multiple correlation between different solar parameters in Medina, Saudi Arabia. Renewable Energy 2007;32:2424–35.

[42] Maghrabi AH. Parameterization of a simple model to estimate monthly global solar radiation based on meteorological variables, and evaluation of existing solar radiation models for Tabouk, Saudi Arabia. Energy Conversion and Management 2009;50:2754–60.

[43] Abdalla YAG. New correlation of global solar radiation with meteorological parameters for Bahrain. International Journal of Solar Energy 1994;16:111–20.

[44] El-Sebaii AA, Al-Ghamdi AA, Al-Hazmi FS, Faidah AS. Estimation of global solar radiation on horizontal surfaces in Jeddah, Saudi Arabia. Energy Policy 2009;37:3645–9.

[45] Sen Z. Simple nonlinear solar irradiation estimation model. Renewable Energy 2007;32:342–50.

[46] Bulut H, Büyükalaca O. Simple model for the generation of daily global solar-radiation data in Turkey. Applied Energy 2007;84:477–91.
[47] Mohandes M, Rehman S, Halawani TO. Estimation of global solar radiation using artificial neural networks. Renewable Energy 1998;14(1–4):179–84.
[48] Mohandes M, Balghonaim A, Kassas M, Rehman S, Halawani TO. Use of radial basis functions for estimating monthly mean daily solar radiation. Solar Energy 2000;68(2):161–8.
[49] Rehman S, Mohandes M. Artificial neural network estimation of global solar radiation using air temperature and relative humidity. Energy Policy 2008;36:571–6.
[50] Rehman S, Mohandes M. Estimation of diffuse fraction of global solar radiation using artificial neural networks. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2009;31:974–84.
[51] Benghanem M, Mellit A, Alamri SN. ANN-based modelling and estimation of daily global solar radiation data: a case study. Energy Conversion and Management 2009;50:1644–55.
[52] Benghanem M, Mellit A. Radial basis function network-based prediction of global solar radiation data: application for sizing of a stand-alone photovoltaic system at Al-Madinah, Saudi Arabia. Energy 2010;35:3751–62.
[53] Kabelac S. Exergy of solar radiation. International Journal of Energy Technology and Policy 2005;3(1/2):115–22.
[54] Hepbasli A, Alsuhaibani Z. Estimating and comparing the exergetic solar radiation values of various climate regions for solar energy utilization. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, in press.
[55] Sahin AZ, Aksakal A, Kahraman R. Solar radiation availability in the Northeastern region of Saudi Arabia. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2000;22(10):859–64.
[56] Petela R. Energy of heat radiation. Journal of Heat Transfer 1964;86:187–92.
[57] Petela R. Exergy of undiluted thermal radiation. Solar Energy 2003; 74:469–88.
[58] Spanner DC. Introduction to thermodynamics. London: Academic Press; 1964.
[59] Jeter SM. Maximum conversion efficiency for the utilization of direct solar radiation. Solar Energy 1981;26(3):231–6.
[60] Samanta B, Al Balushi KR. Estimation of incident radiation on a novel spherical solar collector. Renewable Energy 1998;14(1–4):241–7.
[61] Gunerhan H, Hepbasli A. Determination of the optimum tilt angle of solar collectors for building applications. Building and Environment 2007;42(2):779–83.
[62] Benghanem M. Optimization of tilt angle for solar panel: case study for Madinah, Saudi Arabia. Applied Energy 2011;88:1427–33.
[63] Al-Sanea SA, Zedan MF, Al-Ajlan SA. Adjustment factors for the ASHRAE clear-sky model based on solar-radiation measurements in Riyadh. Applied Energy 2004;79:215–37.
[64] Sayigh AAM. Photovoltaic powered villages in Saudi Arabia. In: IEE Colloquium on energy for isolated communities. 18 May 1988. p. 2/1–4. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=208963, accessed 22 January 2011.
[65] Kettani MA. Photovoltaics in the Arab world. Solar Cells 1982;6(3):234–49.
[66] Salim AA, Eugenio NN. A comprehensive report on the performance of the longest operating 350 kW concentrator photovoltaic power system. Solar Cells 1990;29(1):1–24.
[67] Alawaji S, Smiai MS, Rafique S, Stafford B. PV-powered water pumping and desalination plant for remote areas in Saudi Arabia. Applied Energy 1995;52(2–3):283–9.
[68] Alajlan SA, Smiai MS. Performance and development of PV-plant for water pumping and desalination for remote area in Saudi. Renewable Energy 1996;8(1–4):441–6.
[69] Al Harbi Y, Eugenio NN, Al Zahrani S. Photovoltaic-thermal solar energy experiment in Saudi Arabia. Renewable Energy 1998;15(1–4):483–6.
[70] Hasnain SM, Alajlan S. Coupling of PV-powered R.O. Brackish water desalination plant with solar stills. Renewable Energy 1998;14(1–4):281–6.
[71] Hasnain SM, Alajlan S. Coupling of PV-powered R.O. Brackish water desalination plant with solar stills. Desalination 1998;116:57–64.
[72] Elhadidy MA, Shaahid SM. Parametric study of hybrid (wind + solar + diesel) power generating systems. Renewable Energy 2000;21(2):129–39.
[73] Rehman S, Shash AA, Al-Amoudi OSB. Photovoltaic technology of electricity generation for desert camping. American Journal of Environmental Sciences 2005;1(1):50–8.
[74] Shaahid SM, Elhadidy MA. Economic analysis of hybrid photovoltaic–diesel–battery power systems for residential loads in hot regions—a step to clean future. Renewable and Sustainable Energy Reviews 2008;12:488–503.
[75] Shaahid SM, El-Amin I, Rehman S, Al-Shehri A, Ahmad F, Bakashwain J, et al. Techno-economic potential of retrofitting diesel power systems with hybrid wind-photovoltaic-diesel systems for off-grid electrification of remote villages of Saudi Arabia. International Journal of Green Energy 2010;7(6):632–46.
[76] Rehman S, Al-Hadhrami LM. Study of a solar PV–diesel–battery hybrid power system for a remotely located population near Rafha, Saudi Arabia. Energy 2010;35:4986–95.
[77] El-Sebaii AA, Al-Ghamdi AA, Al-Hazmi FS, Faidah AS. Thermal performance of a single basin solar still with PCM as a storage medium. Applied Energy 2009;86:1187–95.
[78] El-Sebaii AA, Yaghmour SJ, Al-Hazmi FS, Faidah AS, Al-Marzouki FM, Al-Ghamdi AA. Active single basin solar still with a sensible storage medium. Desalination 2009;249:699–706.
[79] Kelley LC, Gilbertson E, Sheikh A, Eppinger SD, Dubowsky S. On the feasibility of solar-powered irrigation. Renewable and Sustainable Energy Reviews 2010;14:2669–82.
[80] Said SAM. Application of photovoltaic systems in Saudi Arabia. Renewable Energy 1992;2(6):587–90.
[81] Radhwan AM, Fath HES. Thermal performance of greenhouses with a built-in solar distillation system: experimental study. Desalination 2005;181:193–205.
[82] Al-Helal IM, Alhamdan AM. Effect of arid environment on radiative properties of greenhouse polyethylene cover. Solar Energy 2009;83:790–8.
[83] Abdel-Ghany AM, Al-Helal IM. Solar energy utilization by a greenhouse: general relations. Renewable Energy 2011;36:189–96.
[84] Huraib FS, Hasnain SM, Alawaji S. Lessons learned from solar energy projects in Saudi Arabia. International Journal of Renew Energy 1996;9(1–4): 1144–7.
[85] Almogren S, Veziroglu TN. Solar-hydrogen energy system for Saudi Arabia. International Journal of Hydrogen Energy 2004;29:1181–90.
[86] Zahed AH, Bashir MD, Alp TY, Najjar YSH. A perspective of solar hydrogen and its utilization in Saudi Arabia. Journal of Hydrogen Energy 1991;16(4):277–81.
[87] Grasse W, Oster F, Aba-Oud H. HYSOLAR: the German-Saudi Arabian program on solar hydrogen—5 years of experience. International Journal of Hydrogen Energy 1992;17(1):1–7.
[88] Abdel-Aal HK. Storage and transport of solar energy on a massive scale: the hydrogen option. International Journal of Hydrogen Energy 1992;17(11):875–82.
[89] Abdel-Aal HK, Hussein IA. Parametric study for saline water electrolysis. I. Hydrogen production. International Journal of Hydrogen Energy 1993;18(6):485–9.
[90] Daous MA, Bashir MD, El-Naggar MMA. Experiences with the safe operation of a 2 kWh solar hydrogen plant. International Journal of Hydrogen Energy 1994;19(5):441–5.
[91] Al-Garni M. Experimental investigations of hydrogen catalytic combustion plates at KACST. International Journal of Hydrogen Energy 1997;22(4):383–7.
[92] Abdel-Aal HK, Al-Naafa MA. Prospects of "solar" hydrogen for desert development in the Arab world. International Journal of Hydrogen Energy 1998;23(2):83–8.
[93] Abaoud H, Steeb H. The German-Saudi HYSOLAR program. International Journal of Hydrogen Energy 1998;23(6):445–9.
[94] Zaidi JSM, Rahman SU, Redhwi HH. R&D activities of fuel cell Research at KFUPM. Desalination 2007;209:319–27.
[95] Al-Sofi MA. Seawater desalination SWCC experience and vision. Desalination 2001;135:121–39.
[96] Thompson C. Summary of administration and management of SOLERAS. MRI/SOLERAS 30001; October 1987.
[97] Khoshaim BK. 200 m^3/day solar sea water desalination pilot plant. Solar & Wind Technology 1985;2(3–4):173–82.
[98] Al-Mutaz IS, Al-Ahmed MI. Evaluation of solar powered desalination processes. Desalination 1989;73:181–90.
[99] Zahed AH, Bashir MD. A case study of a solar energy transfer and storage system in a freeze desalination project in Yanbu, Saudi Arabia. Solar & Wind Technology 1990;7(4):441–6.
[100] Hasnain SM, Elani UA, Al-Awaji SH, Aba-Oud HA, Smiai MS. Prospects and proposals for solar energy education programmes. Applied Energy 1995;52(2–3):307–14.
[101] Hasnain SM, Alawaji SH, Elani UA. Energy education—a viable pathway for sustainable development. Renewable Energy 1998;14(1–4):387–92.
[102] Solar energy technology: present & future. In: 5th Renewable Energy Workshop. 24 April 2010. http://corere.kfupm.edu.sa/reg.html, accessed 20 January 2011.
[103] 2nd Public Lecture Series-Renewable Energy. 24 April 2010. http://corerekfupmedusa/reghtml, accessed 20 January 2011.
[104] Brochure of call. Dhahran, Saudi Arabia: Center of Research Excellence in Renewable Energy; 2010. http://corere.kfupm.edu.sa, 12 p.
[105] Kazmerski LL. Solar photovoltaics technology: no longer an outlier. In: Materials Research Society. 2009 Fall Meeting. Symposium X-Frontiers of Materials Research. 2009. http://www.mrs.org/s_mrs/doc.asp?CID=24787&DID=275677, accessed 20 January 2011.
[106] Kazmerski LL.Power Point Presentation on "Solar Photovoltaics Technology: No Longer an Outlier". 2011. http://corere.kfupm.edu.sa/pres.html, accessed 20 January 2011, 106 slides.
[107] Book T.Power Point Presentation on "Solar Hot Water Applications". 2011. http://corere.kfupm.edu.sa/pres.html, access 20 January 2011, 195 slides.
[108] Sabbagh JA, Sayigh AAM, El-Salam EMA. Research into solar energy utilization in Saudi Arabia. Paris: International Congress on the Sun in the Service of Mankind; 1973. http://www.unesco.org/ulis/cgi-bin/ulis.pl?catno=6913&set=4D415EE0_0_404&gp=1&lin=1&ll=1, accessed 18 January 2011, 10 p.
[109] Sayigh AAM. Saudi Arabia looks at the sun. Sunworld 1978;2:46–9.
[110] Al-Athel SA. Solar energy in the Kingdom of Saudi Arabia. International Journal of Global Energy Issues 1997;9(1–2):53–67.
[111] Rehman S, Halawani TO. Development and utilization of solar energy in Saudi Arabia. Arabian Journal for Science and Engineering 1998;23(1B):33–46 [review].
[112] Elani UA, Bagazi SA. The importance of silicon photovoltaic manufacturing in Saudi Arabia. Renewable Energy 1998;14(1–4):89–94.

[113] Alawaji HA. Renewable energy research, development and applications in Saudi Arabia. In: Renewables: The Energy for the 21st Century World Renewable Energy Congress VI. 1–7 July 2000. p. 1665–8.
[114] Alawaji SH. Life after oil: solar energy research and applications in Saudi Arabia. Refocus 2001;2(2):14–9.
[115] Said SAM, El-Amin IM, Al-Shehri AM. Renewable energy potentials in Saudi Arabia. In: Beirut regional Collaboration Workshop on Energy Efficiency and Renewable Energy Technology. April 2004. p. 76–82.
[116] Rehman S. Saudi Arabian geothermal energy resources—an update. In: Proceedings World Geothermal Congress. 25–29 April 2010.
[117] Fernandez-Garcı A, Zarza E, Valenzuela L, Perez M. Parabolic-trough solar collectors and their applications. Renewable and Sustainable Energy Reviews 2010;14:1695–721.
[118] Mathioulakis E, Belessiotis V, Delyannis E. Desalination by using alternative energy: review and state-of-the-art. Desalination 2007;203:346–65.
[119] Eltawil MA, Zhengming Z, Yuan L. A review of renewable energy technologies integrated with desalination systems. Renewable and Sustainable Energy Reviews 2009;13:2245–62.
[120] Qiblawey HM, Banat F. Solar thermal desalination technologies. Desalination 2008;220:633–44.
[121] Orhan MF, Dincer I, Naterer GF, Rosen MA. Coupling of copper–chloride hybrid thermochemical water splitting cycle with a desalination plant for hydrogen production from nuclear energy. International Journal of Hydrogen Energy 2010;35:1560–74.
[122] Fiorenza G, Sharma VK, Braccio G. Techno-economic evaluation of a solar powered water desalination plant. Energy Conversion and Management 2003;44:2217–40.
[123] Khawaji AD, Kutubkhanaha IK, Wieb JM. Advances in seawater desalination technologies. Desalination 2008;221:47–69.
[124] Qiblawey HM, Banat F. Solar thermal desalination technologies. Desalination 2008;220:633–44.
[125] Charcosset C. A review of membrane processes and renewable energies for desalination. Desalination 2009;245:214–31.
[126] Al-Karaghouli A, Renne D, Kazmerski LL. Solar and wind opportunities for water desalination in the Arab regions. Renewable and Sustainable Energy Reviews 2009;13:2397–407.
[127] Gude VG, Nirmalakhandan N, Deng S. Renewable and sustainable approaches for desalination. Renewable and Sustainable Energy Reviews 2010;14:2641–54.
[128] Mezher T, Fath H, Abbas Z, Khaled A. Techno-economic assessment and environmental impacts of desalination Technologies. Desalination 2011;266:263–73.
[129] Joshi AS, Dincer I, Reddy BV. Exergetic assessment of solar hydrogen production methods. International Journal of Hydrogen Energy 2010;35:4901–8.
[130] Al-Ajlan SA, Al-Ibrahim AM, Abdulkhaleq M, Alghamdi F. Developing sustainable energy policies for electrical energy conservation in Saudi Arabia. Energy Policy 2006;34:1556–65.
[131] Al-Hadhrami LM, Ahmad A. Assessment of thermal performance of different types of masonry bricks used in Saudi Arabia. Applied Thermal Engineering 2009;29:1123–30.
[132] SAW, Saudi Aramco World. A solar village. September/October print edition; 1981. p. 16–29.
[133] Vincent-Barwood A. A solar village. Saudi Arabia and solar energy—a special section; 2011. http://www.saudiaramcoworld.com/issue/198105/saudi.arabia.and.solar.energy.a.special.section.htm, accessed 1 February 2011.
[134] Kim DS, Infante Ferreira CA. Solar refrigeration options—a state-of-the-art review. International Journal of Refrigeration 2008;31:3–15.
[135] Balaras CA, Grossman G, Henning HM, Infante CA, Podesser E, Wang L, et al. Solar air condition in Europe—an overview. Renewable & Sustainable Energy Reviews 2007;11:299–316.
[136] Henning HM. Solar assisted air conditioning of buildings—an overview. Applied Thermal Engineering 2007;27:1734–816.
[137] Tierney MJ. Options for solar-assisted refrigeration-trough collectors and double-effect chillers. Renew Energy 2007;32:183–217.
[138] Parida B, Iniyan S, Goic R. A review of solar photovoltaic technologies. Renewable and Sustainable Energy Reviews 2011;15:1625–36.
[139] Jager-Waldau A. European photovoltaics in world wide comparison. Journal of Non-Crystalline Solids 2006;352:1922–7.
[140] Feltrin A, Freundlich A. Material considerations for terawatt level deployment of photovoltaics. Renewable Energy 2008;33:180–5.
[141] Muneer T, Asif M, Munawwar S. Sustainable production of solar electricity with particular reference to the Indian economy. Renewable and Sustainable Energy Reviews 2005;9:444–73.
[142] Obaid RR, Mufti AH. Present state, challenges, and future of power generation in Saudi Arabia. In: IEEE Energy2030. 17–18 November 2008, 6 p.
[143] Freshfields Bruckhaus Deringer. The renewables market in MENA-opportunities and challenges; Spring/Summer, 2010. http://www.freshfields.com/publications/pdfs/2010/feb10/27386.pdf, accessed 1 February 2011, 27 p.
[144] Taleb HM. Barriers hindering the utilisation of geothermal resources in Saudi Arabia. Energy for Sustainable Development 2009;13:183–8.
[145] Al-Saleh Y. Renewable energy scenarios for major oil-producing nations: the case of Saudi Arabia. Futures 2009;41:650–62.
[146] Patlitzianas KD, Doukas H, Psarras J. Enhancing renewable energy in the Arab States of the Gulf: constraints & efforts. Energy Policy 2006;34:3719–26.
[147] Alsuhaibani Z, Hepbasli A. Future directions of geothermal energy in Saudi Arabia. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, in press.
[148] Hepbasli A, Ozgener O. Turkey's renewable energy sources. 1. Historical development. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2004;26(10):961–9.